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Anna Unt

FIBER LASER AND HYBRID WELDING OF T-JOINT IN STRUCTURAL STEELS

LUT University

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Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 2305 at Lappeenranta University of Technology, Lappeenranta, Finland on the 14th of December, 2018, at noon.

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Abstract

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Laser welding processes are amongst the most versatile joining technologies, suitable for both, small scale and mass production. The advancements in laser sources and optics is allowing autogenous laser beam welding to infiltrate the manufacturing sectors where laser-arc hybrid welding has already replaced traditional joining methods. In order to be successfully applied, fundamental understanding of the process is essential to control the mechanisms affecting the weld formation. This dissertation concentrates on single-sided laser and laser-arc hybrid welding of T-joints in medium thickness structural steels S355 and AH36 with high power fiber laser.

The main research topic in this thesis is the investigation of factors affecting joint geometry formation in laser- and laser-arc hybrid welding of T-joints. Depth, width and surface topology of the weld define the mechanical properties and performance of the joints. Effect of welding parameters on weld profile has been studied using three different optical set-ups. The work aims to understand phenomena behind weld shape variations and to propose means for reducing the complexity of the welding process.

In summary, this work provides considerably enhanced understanding of the formation mechanisms of weld geometries under different processing conditions. The results of this work aim to contribute to expanding the applications of autogenous laser welding processes in manufacturing. Knowledge gained can readily be implemented to practical use, particularly in machine- and shipbuilding industry, where autogenous laser welding could be eligible for wide range of applications.

Keywords: structural steel; high power fiber laser; laser welded joint, laser keyhole welding; T-joint; fillet joint, hybrid welding

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Above all else I am grateful to my Family and close ones, I want you to know how much I value your support.

This thesis is dedicated to the memory of my beloved Father.

Sincerely,

Anna Unt
December 2018
Lappeenranta, Finland

Contents

List of publications

This thesis is based on five scientific publications listed below. The publishers have granted the permission and rights to include these articles in the thesis.

I. Unt, A., Lappalainen, E., and Salminen, A. (2013). Comparison of welding processes in welding of fillet joints. In: Proceedings of The 23^{-rd} (2013) International Ocean (Offshore) And Polar Engineering Conference, pp. 123-145- Alaska: International Society of Offshore and Polar Engineers.

II. Unt, A., Poutiainen, I., and Salminen, A. (2014). Effects of sealing run welding with defocused laser beam on the quality of T-joint fillet weld. *Physics Procedia*, 39, pp. 497-506.

III. Unt A., and Salminen, A. (2015). Effect of welding parameters and the heat input on weld bead profile of a laser welded T-joint in structural steel. *Journal of Laser Applications*, 27, pp. 449-457.

IV. Unt, A., Poutiainen, I., and Salminen, A. (2015). Influence of filler wire feed rate in laser-arc hybrid welding of T-butt joint in shipbuilding steel with different optical setups. *Physics Procedia*, 78, pp. 45-52.

V. Unt, A., Poutiainen, I., Grünenwald, S., Sokolov, M. and Salminen, A. (2017). High Power Fiber Laser Welding of Single Sided T-joint on Shipbuilding Steel with Different Processing Setups. *Applied Sciences*, 7(12), pp. 1276.

The candidate was the main author of all the publications. The candidate carried out the literature study, proposed, conducted and analysed the experiments and is the principal investigator in all publications. All authors discussed the basic structure of the manuscripts, have read and approved the final versions prior to submission for publication. Co-author Ilkka Poutiainen provided the means for making the experiments and contributed by analysing the data. Scientific supervisor Antti Salminen offered guidance with design of the research framework and as a co-author offered valuable comments and suggestions to the manuscripts.

Abbreviations

BPP	Beam Parameter Product
CO_2	Carbon Dioxide
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
HLAW	Hybrid Laser-Arc Welding
HPFL	High Power Fiber Laser
HPSSL	High Power Solid State Laser
ISO	International Organization for Standardization
LBW	Laser Beam Welding
MAG	Metal Active Gas
Nd	Neodymium
YAG	Yttrium Aluminium Garnet
Yb	Ytterbium

Symbol	**Unit**	**Explanation**
A_s	[mm^2]	Beam area on surface of the workpiece
d_{col}	[mm]	Diameter of collimated beam
d_f	[mm]	Focal diameter
E_L	[J/mm]	Line energy (heat input)
E_{SP}	[J]	Specific Point Energy
f	[mm]	Focal length
λ	[nm]	Wavelength
P_L	[W]	Laser power
q_p	[W/m^2]	Power density
t	[mm]	Material thickness
v_w	[m/min]	Welding speed
Θ	[mrad]	Divergence angle
τ_i	[s]	Interaction time

1 Introduction

Important conditions for the progress of industrial manufacturing and mindful production are development and improvement of technological processes of material joining and processing. Autogenous laser beam welding (LBW) and high power laser arc welding (HLAW) are both deep penetration welding processes that produce welds with high depth to width ratio. Autogenous LBW has so far mainly been used in production of tailored blanks in car manufacturing and production of sandwich panels, stack welding thin plates in lap joint arrangement. In thick plate applications, the process of choice has been laser-arc hybrid welding, commonly used for joint types such as butt- and T-joint.

In order to apply either, an autonomous laser beam welding or a hybrid process, several individual parameters or parameter sets need to be considered for a stable welding process and good quality welds. For predicting the weld shape, understanding of the phenomena affecting the formation of the weld bead is essential. Most of the research in welding of T-joints has been carried out using CO_2- and Nd:YAG laser sources that nowadays are falling out of competition with high power fiber and disc lasers. Due to high beam quality of fiber lasers, less power is needed for obtaining same penetration depth, and there are distinct differences during the welding process itself and in geometry of the weld produced.

1.1 Background and motivation

During early years of laser welding technology, the welding industry was conservative to adapt beam based welding processes (Cozens, 2003) (Gerritsen, 2005). The introduction of LBW processes happened gradually as experience and methods of implementation needed to be developed. However, once put in use, the transition from previous welding methods has been fast (Thomy, et al., 2005) (Bachmann, et al., 2016). Currently, the share of laser beam welding is less than one percent of all welding activities. However, it is eligible to replace up to a quarter of them (Simonds, 2016). The investment and operating costs of high power solid state lasers (HPSSL) have been continuously decreasing during last decade, while processing capacity and flexibility of the production have been improving (Assunção, et al., 2010) (Zervas & Codemard, 2014) (Schmidt, et al., 2018).

Traditionally used laser welding systems capable of fulfilling the needs of the heavy industry have been based on CO_2 lasers, which for the long time were the only laser source capable of providing power levels required for joining 10 mm or thicker plates are becoming outdated because of complexity of transporting the beam from source to workpiece via mirrors (Vollertsen & Thomy, 2005). Similarly, Nd:YAG laser based welding systems, regardless of simpler beam manipulation through optical fiber are also losing their relevance because of limited power levels (only capable of producing up to 6 kW) and high operating cost (Howse & Gerritsen, 2003) (Acherjee, 2018). In light of recent technological advancements in high power fiber laser (HPFL) technology, and lack of information about possibilities of welding T-joints with autogenous LBW only, current work is carried out to explore the limitations and propose methods for widening the process parameter window.

1.2 Scope and objectives

Welding long seams and joining large thicknesses in short production times has the highest benefits especially in joining large details as in manufacturing of offshore structures, pipelines, wind turbines and heavy transportation elements (Denney, 2011). The primary focus of majority of the studies on welding with high power, high brightness lasers has been on investigating the methods to increase penetration depth without sacrificing the quality (Kawahito, et al., 2007). Two of the most studied joint types are lap joint and butt joint, while information on welding fillet welds or T-joints is limited, concerning both, LBW and HLAW. Regarding T-joint, the width of the weld has also significant importance. Obtaining fusion throughout the joint plane when welding with high brightness beam is a challenge because welds are narrow. That creates difficulties with tolerances and increases the chance of the weld missing the joint. Determining suitable process parameters is critical for ensuring repeatability and using full advantages of laser beam based welding processes.

The objectives of this dissertation are as follows:

I. Investigation and comparison of industrially applicable welding processes for welding of T-joints in in medium thickness steels.

II. Determining the effect of individual process parameters on the weld profile and proposing methods for parameter optimisation.

III. Investigating the process phenomena responsible for differences in weld geometry with varied optical set-ups utilizing different process fibers.

IV. Improving the quality of the root side through the application of a sealing run welding with defocused beam.

V. Building knowledge on process stability and joint formation while varying the filler wire feed rate in HLAW.

1.3 Thesis structure

This doctoral dissertation is based on five research publications and consists of two parts. The first part provides an overview of welding T-joints with laser and laser-arc hybrid processes and outlines the findings of the papers included in this study. The second part of the dissertation presents five scientific publications.

Chapter 1 covers the background, motivation and research objectives of this study and presents the contribution of the thesis.

Chapter 2 provides an overview of deep penetration laser welding processes and covers the recent developments in welding of structural components with laser beam based processes.

Chapter 3 describes the research methods and states the limitations of this study.

Chapter 4 recapitulates scientific publications included in this dissertation.

Chapter 5 restates the key findings in accordance with research objectives and outlines the interpretations of research findings.

Chapter 6 discusses the implications of research findings and offers suggestions for future work.

1.4 Scientific contribution

This thesis focuses on welding of T-joints with high brightness high power fiber laser. During the scope of work completed the influence of the process parameters on the weld geometry and quality has been investigated. The main scientific contributions of this thesis are:

1) Improved understanding of the relationship between the weld geometry and process parameters based on experimental validation.
2) Defining the critical parameters for welding T-joints autogenously by laser only, and meeting the requirements of quality level B (strict requirements) of ISO 13919-1 standard.
3) Proposing an approach to resolve the problem of the root side quality imperfections through subjecting the root side of the weld to a sealing run welding with defocused laser beam.
4) Workable knowledge base of the welding processes parameters for T-joints by thorough testing of the material qualities AH36 and S355.

These matters are addressed and discussed in more detail in Part II: Publications.

2 State of the art

The main obstacle for reaching high power with any of the previously existing laser types has been cooling of the laser source. What makes fiber laser to stand out among other laser sources is the lack of optical complexity of the gain medium, making it more similar to electrical device rather than to an optical system. This results in tremendous increase in reliability, high wall plug efficiency and better control over beam manipulation. The modular design allows high power levels at price range that is acceptable for modern industry. At current times, only one company is able to manufacture high power fiber lasers (Bachmann, et al., 2016) (Kawahito, et al., 2018) (Schmidt, et al., 2018).

Advantages of high beam quality of modern solid state lasers in a multi-kW range can be significant, concerning preassembly operations, such as welding of sandwich panels and joining structural components in T-joint configuration. Autogenous LBW is one of the least complex welding processes in terms of process variables. High accuracy and precise heat input are realised through control of three main process parameters – laser power, welding speed and size of the focused beam on material surface. Autogenous LBW has several advantages over HLAW because it is a contactless process, and unlike HLAW, does not require production stops for rewiring of the machinery when the steel grade is changed. For example, welding stainless steels or structural steels with arc-based process requires two very different sets of parameters, starting from the dissimilarities in composition of the filler and shielding gas. Ongoing automation and digitalization of manufacturing favours autogenous LBW over HLAW because of a smaller number of process parameters (Katayama, et al., 2012) (Nielsen, 2015) (Fotovvati, et al., 2018). The infrastructure and safety precautions needed for working with a laser already exist in production where a hybrid welding process is used. Together with developments in process monitoring and data handling, significant economic benefits will accumulate from saved time and consumables (Yamazaki & Kitagawa, 2012).

Recent technological developments have brought forward the possibility to broaden the use of LBW in applications that so far have been dominated by hybrid welding. Higher power levels and brighter beams of modern solid state lasers have made possible the use of longer focal lengths, thereby improving the access to the joint and increasing flexibility of the production. Vastly improved depth of field allows carrying out several production stages without moving the workpiece leading to modifications in product design that result in increased service life and reduced ecological footprint (Sproesser, et al., 2017). Applicability to a wide range of materials, small heat input coupled with high joining efficiency (joint cross-section generated per time unit (mm^2/min)) are best utilized in production of large steel structures (Zhang, et al., 2007) (Posch, et al., 2017).

Additionally, the post welding refinement of the weld bead can be done instantly with the same tool, by guiding the defocused beam over the weld as a sealing run to smoothen the weld surface and junctions (Frostevarg, et al., 2014) (Powell, et al., 2015).

Lately, there has been growing interest in methods involving the manipulation of beam power density on the surface of the workpiece. The processing parameter window can be increased via beam shaping, splitting and oscillation techniques (Schaefer, et al., 2017) (Laskin, et al., 2018) (González & Pozo, 2017). Concurrently, research focus has been on developing the technologies for joining components with difficult access (Kristiansen, et al., 2017), (Zhang, et al., 2018), (Levshakov, et al., 2015) and increasing the process stability by altering the physical processing conditions (Li, et al., 2018), (Üstündağ, et al., 2018), (Bunaziv, et al., 2017).

2.1 Industrial background

Increasing the manufacturing efficiency and reducing the environmental impact are becoming more and more important in modern metalwork production. Fusion welding is an extensively used fabrication method and process optimization in such an early production stage results in reduced cost and duration of manufacturing, while having a positive impact on the service life of the product (Fricke, et al., 2015). In the last 10 years, laser based hybrid welding processes have been replacing expensive and time consuming conventional arc welding techniques in machine building, shipbuilding, offshore structures and transportation industry (Grünenwald, et al., 2010), (Acherjee, 2018).

First guidelines concerning laser welding were published in 1996 by European Ship Classification societies, in 2005 the hybrid welding process was also included (Nielsen, 2015). European shipyards were pioneers of the hybrid laser arc welding application in panel production. In 2005, a 10 kW fiber laser was used for the first time in a shipyard environment by IMG GmbH for joining 6 mm thick plates at 3.2 m/min (7.8 kW) and 10 mm plates at 1.5 m/min (10 kW) respectively (Kessler, 2007). Extensive research on process optimization followed. R&D projects such as SHIPYAG, NORLAS, NORHYB (Gerritsen, 2005), HYBLAS (Kristensen, 2009) were concentrating on shipyard needs specifically. Better understanding of the process, emergence of new laser sources such as disk and fiber laser and decreasing price per kW has led to worldwide adopting of HLAW (Koga, et al., 2010), (Koji Gotoh, 2016), (Bachmann, et al., 2016).

Gas metal arc welding (GMAW) processes that have been conventionally used for the production of several meters long and straight welds introduce a lot of heat into the base material. When the joining speed of different welding methods is discussed, it is often mentioned that automated arc welding processes provide welding speeds in the range of 0.2 to 2.0 m/min, while not mentioning the circumstances which make this number relevant or comparable. In practice, regarding material thicknesses above 2 mm, the speeds at the lower end of the mentioned range are predominant. In preassembly operations, such as welding of sandwich panels and joining structural components, about 80 % of welds are fillet welds (Howse & Gerritsen, 2003). The Application of laser based welding processes contributes towards reducing the overall weight of the whole construction, while not compromising the structural integrity (Lillemäe, et al., 2017). Figure 1 shows CO_2-laser-arc hybrid welding production line for the pre-fabrication of 20 m long deck panels (Moeller & Koczera, 2003) (Reisgen, et al., 2013).

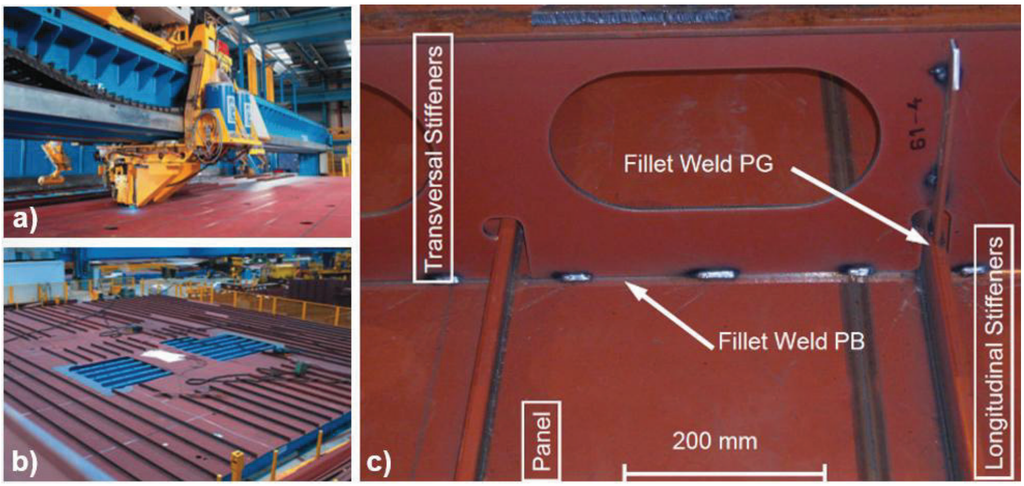


Figure 1. Production of deck panels at Jos. L. Meyer GmbH, Papenburg: a) HLAW setup to weld stiffeners; b) finished panel; c) fillet welds (T-joints) needed for joining stiffeners.

Stiffener plate thicknesses remain generally between 4.0 and 8.0 mm (Staufer, 2013), as specified by the design guidelines for arc processes. The reason behind thickness limitations is the large heat input of arc processes, which limits the minimum possible plate thickness due to probability of distortions. Details like stiffeners require welding with arcs from both sides to balance out the heat distortions. This causes heat-induced distortions and the need for post weld straightening and corrective work. For example, replacing traditional arc welding processes with HLAW has led to five times smaller production costs. The number of welding runs needed is less, because full penetration is possible even with a single-sided access to the joint. (Turichin, et al., 2017) (Neubert & Kranz, 2013). Post weld straightening and corrective work alone are estimated to consume around 30 % of labour time in hull manufacturing (Levshakov, 2014). The distortion effect is influenced by the size of the workpiece so that the distortion increases with increasing length (Froend & Kashaev, 2015). Figure 2 displays the comparison of deformations calculated for arc welding and HLAW. It has been shown that the use of HLAW decreases weld distortions at least by 50 % (Koga, et al., 2010).

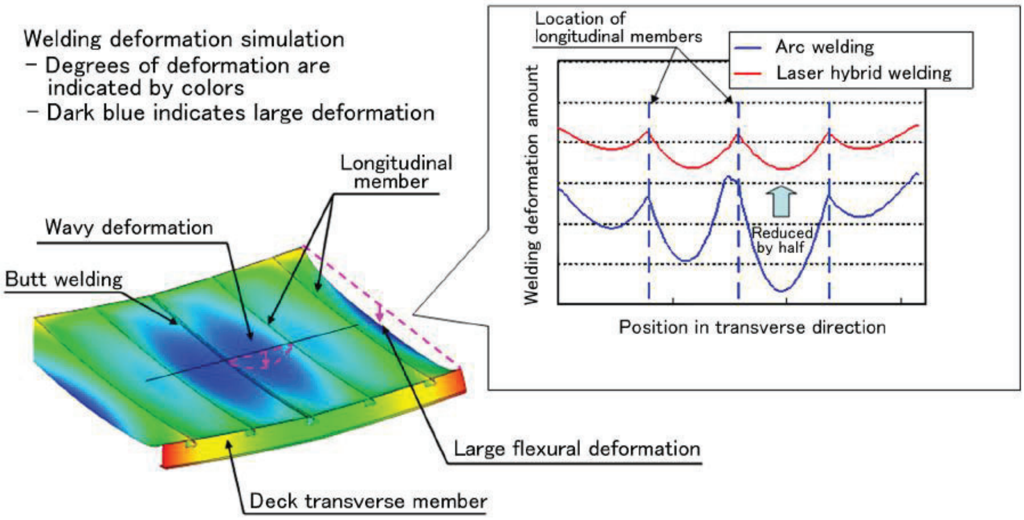


Figure 2. Calculated heat distortions for butt and fillet welds produced with arc and laser hybrid welding processes (Koga, et al., 2010).

The investment and operating costs of high power fiber and disk lasers (and price per kilowatt of laser power) have been continuously decreasing during the last decade, while processing capacity and flexibility of the production have been improving (Kincade, et al., 2018), (Overton, et al., 2017). High beam quality allows the use of processing lenses with long focal length which means larger working distances and better joint access while avoiding damage to optical components. Steel structures with plate thicknesses under 8 mm are especially suitable for joining with autogenous LBW, provided welds meet the requirements of mechanical properties (hardness, fatigue etc.) (Woloszyn & Howse, 2001). Research on deep penetration laser- and laser-arc hybrid welding is carried out in research centres around the world: Japan (Osaka JWRI), Germany (BIAS, Fraunhofer IWS, BAM, ISF RWTH-Aachen), United Kingdom (Universities of Cambridge, Cranfield), Russia (SPbSPU, ILIST, MEPhI) Sweden (LTU), Finland (Aalto, LUT, Oulu Universities and VTT).

2.2 Overview of laser and laser-arc hybrid welding

Laser beam as a tool for deep penetration welding can be used autonomously or in combination with one or more conventional welding processes. The distinctive feature of laser welds is the deep penetration, only comparable with that of an electron beam. Penetration depth is however not the most special characteristic of fiber laser welding, the most remarkable feature is the capability of producing welds with nearly parallel side walls. (Bachmann, et al., 2014), (Thomy, et al., 2005), (Casalino, et al., 2010). This is of critical importance, especially when the dimensions of workpiece are large, as a weld having almost rectangular cross section does not cause angular deformations in the structure, meaning that what was flat remains flat and what was round, remains round. For special applications with stringent quality requirements, severely restricted access or a hostile environment, laser welding is a very suitable joining method (Fabritsiev, et al., 2018). LBW is competitive with HLAW (which already has replaced arc processes in many applications) in welding sheet thicknesses up to 8 mm. Compared to GMAW, laser- and laser-arc hybrid welding processes have several advantages when joining structures in medium and high plate thickness (Olsen, 2009) (Casalino, et al., 2010) (Turichin, et al., 2017):

- high welding speed (2-3 m/min) and process stability during welding
- high joining efficiency (up to 20 mm thick plates can be joined in a single pass with 1.5-2 m/min)
- small heat input and narrow heat affected zone, shorter cooling times
- less need for groove preparation/beveling
- preheating is usually not required
- greatly reduced consumption of filler material
- repeatability and consistent weld quality
- greatly reduced heat deformations and post-weld residual stresses.

In principle, if single processes are compared, any laser based welding system has at least three times the productivity of arc processes which might be considered as an alternative. The price per meter of the weld is higher, however, the above mentioned advantages override the simple price-per-meter calculation, because of higher joining efficiency and better mechanical properties (depending on material) that any other welding process is capable of reproducing. Characterisation of the LBW and HLAW and comparison of the processes is presented in Table 1 (Ono, et al., 2002) (Olsen, 2009), (Ahn, et al., 2017).

Table 1. Summary of properties of LBW and HLAW

LBW	HLAW
Advantages compared to HLAW: • non-contact processing, no tool wear • compact size of processing unit • low maintenance • minimal down-time and fast set-up of welding task when material or detail changes • small number of adjustable process parameters (laser power, welding speed, focal point position) • one-sided access to workpiece • possibility to optimize design, reduce weight and save material • no consumables (shielding gas or filler) • if needed, preheating and post-weld surface improvement can be done with same laser and optical setup • rapid cooling produces fine-grained weld microstructure, which is especially relevant in joining high strength steels.	**Advantages compared to LBW:** • lower requirements for part preparation • higher processing speed • compensating for possible part misalignment or gap fluctuation • increased utilization of beam energy in material • possibility to control mechanical and metallurgical properties of the joint through addition of filler material and control of the cooling rate
Disadvantages compared to HLAW: • strict requirements for joint fit-up • regarding thick materials, fast cooling rates may result in formation of brittle microstructures and hot cracking. • at equal welding speed, considering meters of weld produced in a minute, LBW is less productive than HLAW	**Disadvantages compared to LBW:** • large number of process parameters • expenses on consumables • longer down-time for re-calibration of equipment when material or task is changed • sensitivity to magnetic fields • sensitivity to processing atmosphere and necessity to use shielding gas

2.3 Effect of beam characteristics on the welding process

High brightness solid state lasers have been replacing CO_2 laser based welding systems that have previously been used for HLAW (Bachmann, et al., 2016). In addition to better focusability and simpler beam transmission systems, solid state laser radiation (1030-1080 nm) has a higher absorption coefficient in steel and does not necessarily require the use of shielding gas as a smaller plasma plume is generated (Katayama, et al., 2010) (Li, et al., 2014). Smaller sensitivity to plasma shielding effects, benefits the formation of the weld geometry (Rominger, 2011) (Fellman, et al., 2004).

Without the "plasma shield", compared to CO_2 laser beam having the same spot size and power density, a higher amount of energy is coupled into the material (Weberpals, et al., 2007). The beam of high power multimode fiber lasers equipped with step index fiber for beam delivery has a top hat profile at its focal point. The top hat beam profile has a more even energy distribution than a Gaussian beam, which leads to faster melt flow inside of the keyhole and under the same parameters produces an increased penetration depth and differences in weld dimensions. (Haug, et al., 2013) (Eriksson, et al., 2011). High power solid state lasers deliver a tightly focused beam unreachable by other laser types, and for a given speed - power combination, achieve a 50-100% increase in welding speed and deeper penetration in comparison to other solid state lasers (Popov, 2006).

In laser processing, the size of the area where the beam is focused usually is described as the diameter of the cross section of the beam at the focal point. The beam quality and intensity is of importance, as the laser beam needs to be focused at a certain distance. For generating a keyhole to perform deep penetration welding, an intensity of at least 10^6 W/cm² is needed (Ion, 2005) To achieve such intensities, a small focal diameter (d_f) is desired. Regarding equation (1),

$$d_f = \frac{M^2 f 4}{d_{col} \pi} \lambda \tag{1}$$

this can be done by applying a short focal length f, a small beam quality factor M^2, a large diameter of collimated beam d_{col} on the focal lens and a short wavelength λ. When choosing optics for a certain welding task, the focal length and the diameter of the collimated beam on the focal lens are given parameters. With the wavelength dependent on the laser source, the only parameter left to vary is the beam quality factor M^2 determined as the ratio of the beam parameter product BPP of the actual beam to that of an ideal Gaussian beam of the same wavelength. The smallest possible value of M^2 is 1, for a diffraction limited Gaussian beam. However, for higher transversal modes, the focal diameter d_f as well as the beam divergence angle θ are increased by the factor M, leading to equation (2) for the relation of BPP:

$$d_f = \frac{\pi}{\lambda} BPP \tag{2}$$

The BPP itself can be calculated from equation (3):

$$BPP = \frac{d_f \theta}{4} \tag{3}$$

where θ is the beam divergence angle. From these equations it can be seen that with good beam quality (smaller BPP, or, M^2 value closer to 1) the focal length can be increased by keeping the focal diameter constant and retain the required intensity on the workpiece. Figure 3 illustrates the effect of different beam parameter products on the diameter and focal length of the focused beam.

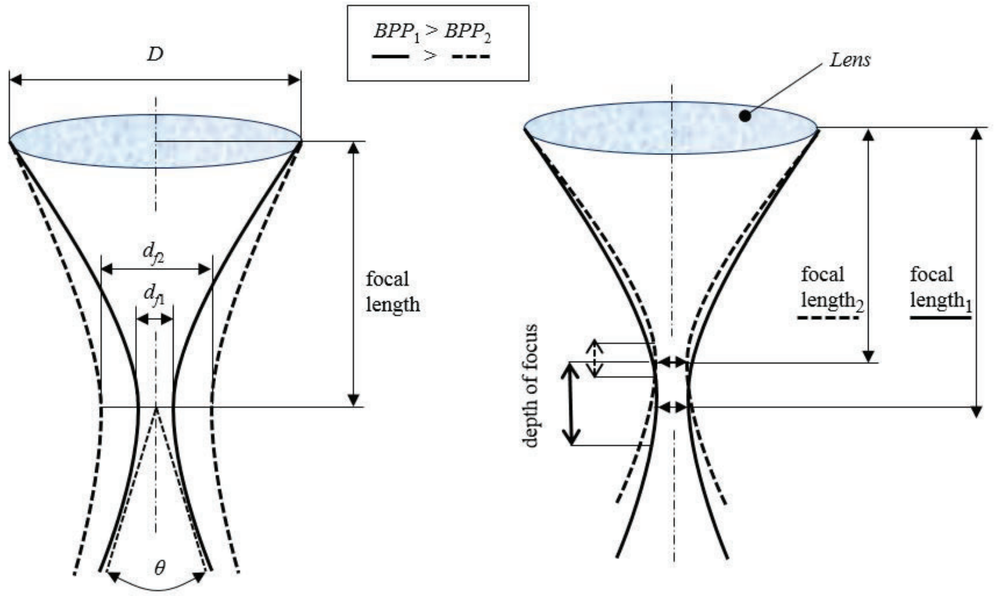


Figure 3. Advantages of lasers with high beam qualities (BPP1 > BPP2) leading to smaller focused spot diameters with higher intensities (left, f constant), or longer focal length with constant focal diameter (right, d_L and d_f constant).

High power fiber lasers have both, high irradiance, and, beam delivery by optical fiber. Beam qualities smaller than 10 mm·mrad, have been reached at power levels up to 20 kW and beyond, therefore making them suitable to be used for thick section welding. (Shi, et al., 2014). Uniform power distribution contributes to process stability regardless of the diameter of the focused beam or dimensions of the keyhole it creates. A top hat beam has Gaussian-like power distribution outside of the focal plane. Expanding the beam size on surface by defocusing in either direction is not a viable alternative, because in addition to loss of power density and disturbance of the process by plasma, the risk of back-reflections that may damage the process fiber is increased. The effect of beam quality of two different solid state lasers on joint geometry can be seen from Figure 4.

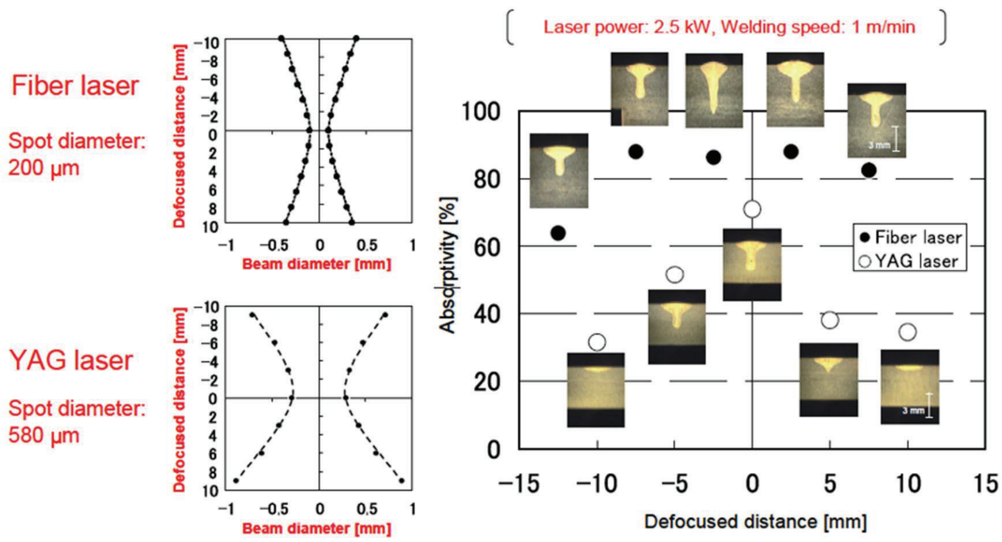
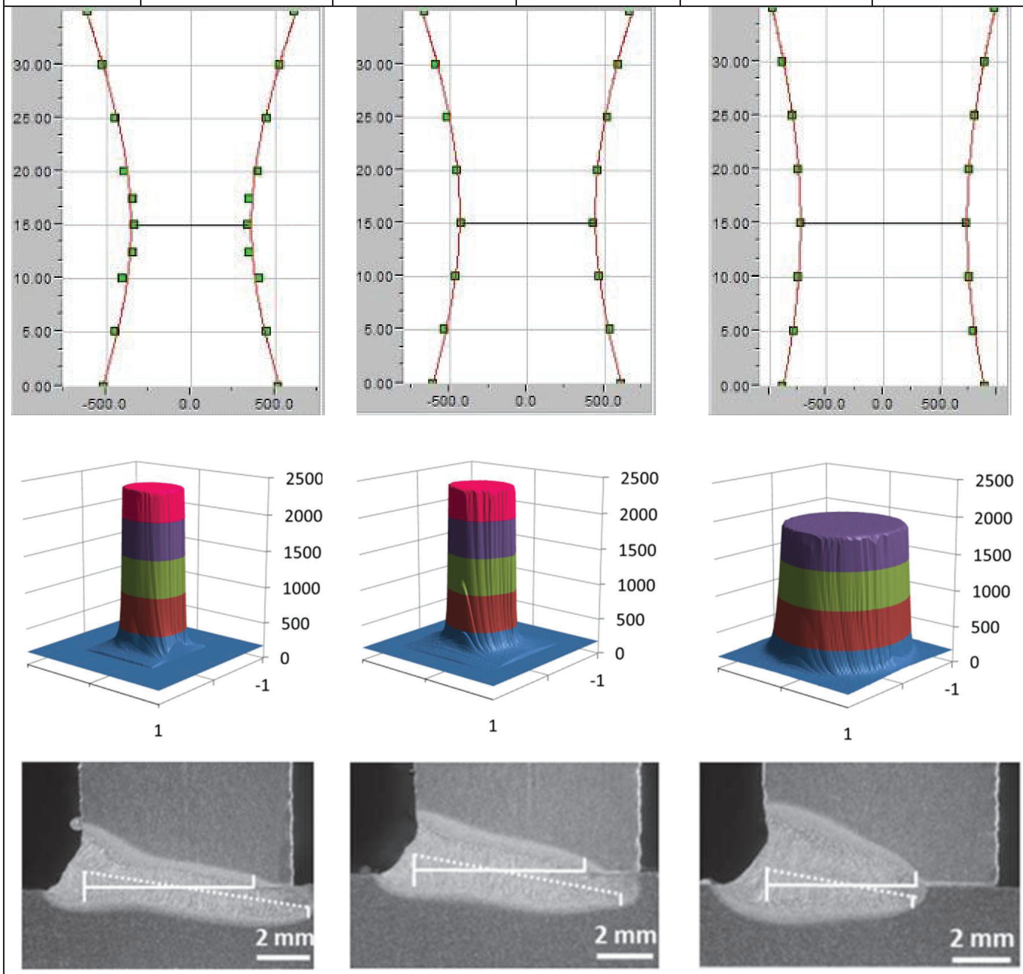


Figure 4. Absorption differences of fiber laser and Nd:YAG laser welds in SS304 stainless steel as a function of focal point displacement: (Katayama, et al., 2012). The effect of beam quality on the weld geometry and the advantage of long focal lengths are clearly visible.

From Figure 4 it can be seen that minor focal point misalignments of the fiber laser beam do not cause obvious changes in the weld shape or the depth of penetration. To expand the applicability of laser beam welding to T-joints in thicknesses relevant to transport and machine building industry, the width of the weld has to be increased as well, especially at the root of the weld. This is only possible through increasing the volume and dimensions of the melt pool. Therefore, distributing high power high brightness beam on larger surface area will create a larger keyhole and therefore a weld that is wide throughout the whole penetration, assuming that enough laser power is available. Table 2 is created based on experimental work carried out for *Publication V* and displays the characteristics of the laser beams and corresponding welds produced under same processing parameters.

Table 2. Caustics of the beams used during the study and corresponding weld profiles

Delivery fiber core diameter [µm]					
200 µm		**300 µm**		**600 µm**	
Ø [mm]	area [mm^2]	Ø [mm]	area [mm^2]	Ø [mm]	area [mm^2]
0.710	0.396	0.882	0.611	1.460	1.674



AH36, t = 8 mm, P_L = 6 kW, v_W = 1.25 m/min, FPP = -2 mm, angle from flange 10°
solid line – effective throat length; dashed line - penetration depth

In laser and hybrid welding of T-joints the alignment of fusion area in respect to joint plane has been an issue due to narrow weld. To implement autogenous laser welding for joining medium- and thick sections in a T-joint, the width of the weld has to be increased, especially at the root of the weld.

2.4 Formation of the weld shape and melt pool

In laser keyhole welding, the high intensity beam evaporates the material and forms a so called keyhole which is a cavity that is kept open by the surface tension of the material. The dimensions of the keyhole and melt flow within are influenced by characteristics and energy distribution of the laser beam (Fotovvati, et al., 2018). Flow patterns that occur in keyhole welding depend on the intensity of the incoming beam and properties of the liquid metal (Fabbro, 2010). Keyhole behaviour determines the dimensions and quality of the resulting weld (Fabbro, 2010), the process is schematically illustrated in Figure 5.

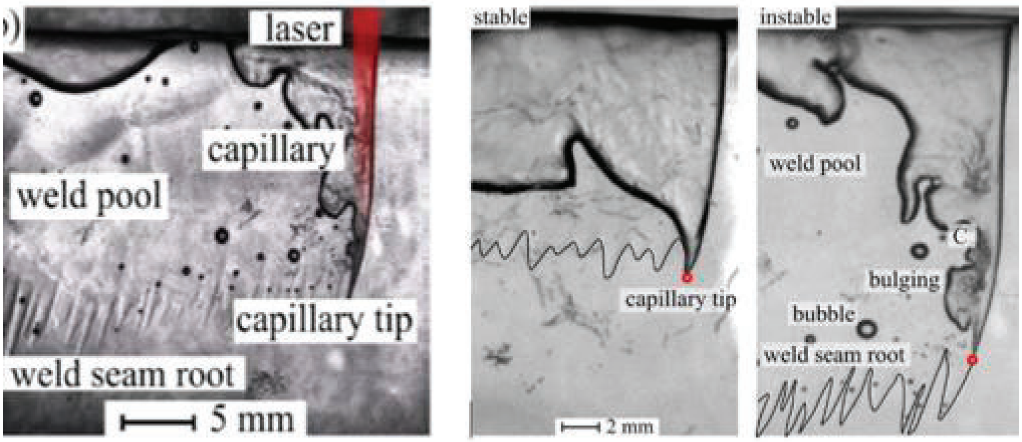


Figure 5. Schematic representation of weld pool and bead formation on the example of keyhole laser welding of ice (Fetzer, 2018).

The three main input process parameters of LBW are laser power, welding speed and focal distance, which can be controlled rather efficiently (Mazmudar & Patel, 2014) (Kawahito, et al., 2007) (Ion, 2005). Regarding T-joints, the small width of the laser welds is a challenge for the production of full fusion welds throughout the joint length. Melt pool and therefore the width of the weld can be enlarged either by welding with oscillated beams, or by expanding the beam area on surface by applying different optical arrangements. General influences on weld geometry regarding both, LBW and HLAW are as follows (Shcheglov, et al., 2011) (Li, et al., 2015):

- effect of gravity – welding position, e.g. flat or horizontal, affects melt flow and solidification, although in horizontal position flange acts as a root support.
- effect of gap bridging – in LBW a technical air gap of 0 mm is preferred, in HLAW a small gap promotes deeper penetration and aids in mixing of filler wire deeper into the keyhole
- effect of focal point position in respect to material surface – thick sections are welded with FPP inside the material. A focus below the material surface increases penetration depth, whereas focusing above the surface leads to power losses due to plasma generation above the keyhole and results in decreased penetration.

Effect of laser power: The applicable power level is usually limited by the equipment available and has the most profound effect on the penetration depth. A higher power achieves a deeper the penetration and allows increasing the welding speed, since the heat input is also increased. The higher the laser power, the more control is needed to keep the process stable, especially in thick section welding. High laser power produces high penetration, but additional measures e.g. preheating, melt pool support, are usually required to ensure the stability of the process (Jiang, et al., 2017) (Kawahito, et al., 2018) (Artinov, et al., 2018).

Effect of welding speed: At power densities sufficient for creating keyhole, the welding speed has an effect on both, penetration depth and width of the weld. For each beam power density an optimal range of welding speeds exists. Low welding speeds produce deeper penetration and wider welds, with an increase of the welding speed both, depth and width decrease. However, the depth to width aspect ratio increases, as the penetration depth is determined predominantly by the power density of the beam. At too low welding speeds, the process becomes unstable. Heat conduction ability of the material is limited, and an excess of melt will lead to a keyhole collapsing, spatter, severe undercut formation on the face side and possible melt drop out on the root side. Too high welding speed causes keyhole instability and leads to uneven penetration, spatter, formation of porosity and depending on the material thickness, increases the likelihood of solidification cracking and occurrence of brittle microstructures (Fabbro, 2010) (Li, et al., 2014).

Effect of focal point size and position: For lasers using optical fibers to deliver the beam, the size of the focused beam is dependent on the core diameter of the transfer fiber and the ratio of the focusing lens focal length to collimation focal length. Wider beams have a longer Rayleigh length and a greater tolerance to both, the positioning of the beam in respect to the joint interface, and, the changes in FPP in respect to the material surface. The focal point position relative to the surface affects the power density of the beam on material surface and therefore has an effect on the dimensions of the keyhole and stability of the process. Regarding the weld seam geometry, the penetration depth and the molten pool area, the variation of the focal point position has a tertiary influence, after laser power and welding speed (Weberpals, et al., 2006) (Matsumoto, et al., 2017) (Enz, et al., 2015).

2.5 T-joints

T-joints in form of T-butt or fillet connection is the most common joint type in structural welding, and commonly not a load-bearing connection (Cozens, 2003) (Hobbacher, 1997). A T-joint is welded using the smallest possible angle from the junction that dimensions and construction of the welding head allow. Depicted on Figure 6 are the critical dimensions of deep penetration fillet welds and characteristic weld profiles of LBW and HLAW welds.

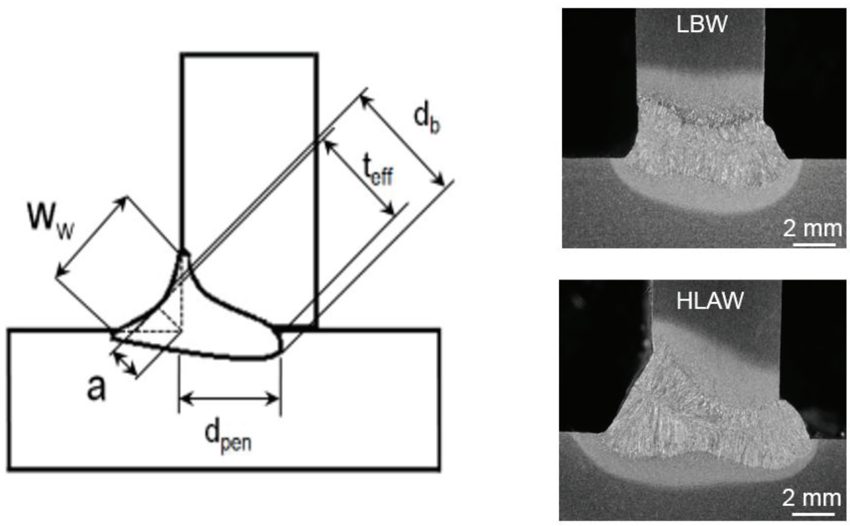


Figure 6. Weld geometry dimensions (left) and typical macro-sections of laser (upper) and hybrid (lower) welded joints performed from one side in a single pass.

In autogenous processes, the joint is formed from the material of the fitted plates. The beam is positioned slightly above the joint interface on the web and its alignment in respect to the joint plane has to be very accurate. This holds importance also in HLAW, because deep penetration is created primarily by the beam. With faulty beam alignment the weld shall miss the joint interface. Arc energy source and filler wire brought to the process will be beneficial for bead surface quality, but are not penetrating deep enough into the melt pool to aid the formation of the root of the weld. The cross-section profile of the joints produced with laser and hybrid welding differs from conventional GMAW welds. The mechanical properties of the joint and its load-carrying ability are determined by extent of fusion along the joint plane, instead of height of the reinforcement of the weld metal deposits on surface (Björk, et al., 2018).

Deep penetration laser and hybrid welding are accompanied by the appearance of porosity and formation of the bead surface irregularities when the processing conditions are not optimal (Zhang, et al., 2018). According to prevailing insights of physical phenomena accompanying laser welding processes, these irregularities are formed when the keyhole is unstable and the dynamics of the melt pool is disturbed (Chen, et al., 2017) (Stavridis, et al., 2018) (Fabbro, 2010). Potential flaws most likely to occur when welding T-joint in structural steels are:

- visible geometrical defects like undercut (caused by wrong parameter choice).
- weld missing the joint plane (caused by incorrect beam positioning).
- lack of material in the weld (caused by gap fluctuations during long welds).
- porosity (caused by keyhole instability and fast solidification at high welding speeds when gas bubbles are not able to escape the melt pool).
- hot cracking (caused by high cooling rates, likelihood grows with material thickness).
- spatter (caused by excessive welding speed).

The concerns that justify the use of HLAW for joining thick plates in butt joint are of smaller significance in welding of T-joints. First of all, the likelihood of hot cracking is lower, because heat distribution in material and resulting weld microstructure are more uniform than in welds produced in thicker material. Secondly, full fusion of the joint plane in 4-8 mm thickness is possible in a single pass. Thirdly, the flange supports the melt pool, therefore issues with melt dropout or weld sagging are less likely to appear. Taking all previous into account, the necessity of filler wire and additional heat sources can be questioned. The need for alloying filler material is a subject of debate when thin plates are joined, because control of the heat input in autogenous laser welding involves smaller number of process parameters and is more precise and simpler than in hybrid welding. In addition, HLAW is a more expensive process with lower productivity, because in most cases it predicates the groove preparation by beveling and maintaining the air gap in the joint. With tight clamping, these steps can be avoided and weld can be produced autogenously.

3 Research methodology

Subjects of investigation in this doctoral thesis are presented in five research publications published in scientific journals and conference proceedings. All research objectives required an experimental study. Together with providing the review of the state of the art literature, the primary focus of the thesis is on understanding the influence of process parameters on the resulting weld geometry and proposing ways for process optimization and broadening the parameter window.

3.1 Materials and methods

All of the welding experiments included in this study were carried out using a 10 kW fiber laser (IPG YLS-10000) equipped with a Kugler LK190 mirror optics welding head having a 150 mm collimation and 300 mm focal lens. The manipulation of beam properties was done by changing the beam delivery fiber, fibers with core diameter 200, 300 or 600 µm were used.

In HLAW, the Kugler laser welding head in combination with a Binzel MAG torch and a Kemppi ProMig power source set to pulsed arc mode were used with synergy setting on. The beam-arc process distance was kept constant at 3 mm. Shielding gas Ar+18%CO_2 was delivered at 20 l/min flow rate through the MAG torch.

The materials used in the experiments, construction steel S355 and shipbuilding steel AH36, are two most widely used materials in structural fabrication. Workpieces with 8 mm thickness were CO_2-laser oxygen cut and sheet edges were grid blasted and cleaned with acetone before welding. Both materials have low carbon content and are known to be weldable by laser. The chemical composition and the mechanical properties are shown in Table 3.

Table 3. Chemical composition of the materials.

Ruukki Laser 355MC				
Chemical composition (wt%)				
C max	Si max	Mn max	P max	S max
0.055	0.1	0.69	0.006	0.005
Mechanical properties				
Yield Strength (R_{eH}), MPa		Tensile Strength (Rm), MPa		Hardness, HV
355		430-530		235
AH36				
Chemical composition (wt%)				
C max	Si max	Mn max	P max	S max
0.18	0.03	0.7	0.035	0.035
Mechanical properties				
Yield Strength (R_{eH}), MPa		Tensile Strength (Rm), MPa		Hardness, HV5
355		430-530		180

To describe the energy input of laser welding process, two approaches were used. Firstly the line energy (E_L) concept, that follows an example with a formula used to calculate heat input in conventional welding processes. It is calculated based on laser power and welding speed as follows:

$$E_L = \frac{P_L}{v_w} \quad (4)$$

The second method utilized was the Specific Point Energy *(E_{SP})* concept, originally developed to simplify the comparison of different laser processing systems (Suder & Williams, 2012). In addition to power-speed relationship, this approach accounts for beam-material interaction time τ_i and beam area A_s on surface of the workpiece. E_{SP} makes an assumption that beam profile on surface is rectangular, however it still is appropriate for predicting the dimensions of the weld bead produced with top hat beams having small focal diameter. E_{SP} is calculated by equation (5):

$$E_{sp} = q_p \tau_i A_s = P\tau_i \quad (5)$$

The welds were visually inspected for flaws, subsequently macrosections were taken, polished, etched and macrographs were analyzed with ImageTool software. Hardness measurements were carried out with Struers Durascan 70 using 500 g load (HV5).

3.2 Research limitations

- The findings of this study are limited to structural and shipbuilding steels with well-known mechanical properties and predictable behavior in fusion welding processes.
- In this thesis, materials are limited to S355 and AH36 steel grades. Majority of experiments have been performed on 8 mm thick AH36 plates in 2F (horizontal) welding position.
- The experimental setup used for HLAW consisted of fiber laser-MAG processes only, excluding hybrid configurations of all other laser types and arc processes.
- The factors affecting the formation of weld microstructure have not been addressed in depth. The characterization of mechanical properties of the joint has been limited to hardness measurements. Calculations predicting the fatigue behavior of the joints based on weld geometry remain out of the scope of this study.

4 Overview of the publications and research findings

This chapter summarizes the objectives, results and main contributions of five research papers that form the second part of this thesis. The relation of publications to research objectives (presented in subchapter 1.2) is summarised in chapter 5.

4.1 Publication I

Comparison of welding processes in welding of fillet joints

Objective

The purpose of Publication I was to collect data and build knowledge about the efficiency of a fiber laser based welding setup in welding of T-joints. Previous studies have shown that high power solid state lasers with high brightness beams produce welds with characteristics that differ from welds made with laser sources with poorer beam quality. Existing research was heavily concentrated on increasing penetration depth in welding butt- and lap joints, while T-joints, regardless of being a common connection type, had been addressed rarely. Flat (1F or PA) welding position was chosen as it was most suitable for evaluating the capability of the system. The aim of the study was to observe the effect of the process parameters and heat input on the quality of the weld and geometrical aspects of the welds produced with LBW and HLAW.

Results

First and foremost, the publication discusses the effects of laser power, welding speed, beam inclination angle in both processes. In HLAW, the orientation of the processes and rate of filler wire addition were subject of this investigation. As expected, at a comparable heat input both processes produced joints with higher strength than arc welding even when full penetration was not achieved. Welds fitting the B level of quality according to the standard of laser-arc hybrid welding of steels were produced in 8 mm thickness. In HLAW, leading arc arrangement produced a smoother weld toe compared to laser leading process. All welds had highest hardness values at the root, which is explainable by faster cooling rate. Tensile tests showed that fracture occurred in weld zone of partial penetration welds and was caused by porosity. Full penetration laser weld did not break even when the web was pressed to the flange.

Contribution to the whole

Paper I focused on the weld morphology achieved by different processes. Defining a parameter window for full penetration was attempted. Welds produced with LBW had the highest hardness values throughout the joint, but did not break during the bend test where force is applied on the web to bend it over the flange. This gives evidence that critical hardness levels stated in standards are not necessarily a reason for quality rejection of laser welds. Based on experiments performed in this study, laser welded joints kept the integrity under load, likely reason being the fine-grained microstructure, bending over web-to-flange without breaking. The process arrangement in HLAW did not have a significant effect on the penetration depth because welds were produced in flat position. Findings of this study were subsequently used as a reference basis for welding in horizontal position that is the most common in production.

4.2 Publication II

Effects of sealing run welding with defocused laser beam on the quality of T-joint fillet weld

Objective

Publication II explored the applicability of sealing run welding to improve root side quality of T-joint. Flaws such as incomplete penetration, partial penetration, or undercuts and excess of melt pushed through in full penetration can be eliminated immediately after completing the welding pass by guiding a defocused beam along the newly produced weld seam.

Results

Welds with incomplete and excessive penetration were produced and subsequently treated with running a defocused laser beam over the irregularities on the root side. The beam was moved upwards out of the focal plane to change the spot size on the workpiece surface, inclination angles from 6° to 45° were tested. Significant decrease or even complete elimination of the root side irregularities was achieved. The root side of the weld is a possible location for cracks to appear, running over it with defocused beam “seals” the joint and creates smooth junction between web and flange.

Contribution to the whole

The second paper investigated the means of improving geometrical faults and optimisation of weld geometry through subjecting the welds to post-treatment with a low power laser beam. Re-melting of the solidified droplets during sealing run welding smoothened the surface and increased the quality of the root side regardless of its initial state. It was shown that flaws such as irregular melt formations and lack of fusion on the root side can be eliminated. Improvement in quality transfers to an increased reliability and longer fatigue life under service. It was concluded that the defocused beam is an efficient, simple and straightforward tool for improving the joint quality.

4.3 Publication III

Effect of welding parameters and the heat input on weld bead profile of a laser welded T-joint in structural steel

Objective

In the third publication, laser and laser-arc hybrid welding of 8 mm thick AH36 was studied in flat and horizontal welding positions. The subjects of the study were focal point position, beam inclination angle and heat input. Additionally, the comparison of the weld geometry of T-joints welded with CO_2 laser was made.

Results

The topics of interest of this study were to expand the knowledge presented in publication I to horizontal welding position. A comparison with previous studies of welding T-joint with CO_2 and Nd:YAG laser was made. Full penetration joints with high depth to width ratio, small HAZ and good quality on both sides were produced. Welds produced in flat position had a slightly deeper penetration, which is explainable by the effect of gravity on the liquid melt. Because of the small width of the fusion zone, the approach angle of the beam for full penetration is limited to 6°. The focal point was positioned 2 mm above, 2 mm below and on the surface of the specimen. It was confirmed that the penetration is deeper when the FPP is below the surface, however the bead sank inwards more than 1 mm. Considering HLAW, placing the FPP inside of the material is beneficial, because the filler wire brings additional material to produce a bead with a good profile. In autogenous processing, positive defocusing produced welds with smoothest top bead without apparent undercut or sinking.

Contribution to the whole

The third publication investigated the effect of process parameters and welding positions on the formation of the joint shape. Comparison of results with existing data confirmed that different laser sources produce different shapes of weld cross-sections. Higher seam quality of CO_2 laser welds described in literature is explained by distortion of the beam by plasma, which gives similar effect as defocusing of a fiber laser beam above the surface would. Analysis of macrographs of the weld cross-sections showed that the weld made with a fiber laser propagates strictly along the angle of the aimed beam at all times, penetrating the base plate when the beam is aligned improperly. The laser power has the strongest effect on the penetration depth. Width of the weld is correlated to welding speed. A higher heat input increases the width of the weld and decreases hardness. Hardness of HLAW welds was lower than in LBW welds, remaining under the critical level of 380 HV5 at welding speeds under 2 m/min.

4.4 Publication IV

Influence of filler wire feed rate in laser-arc hybrid welding of T-butt joint in shipbuilding steel with different optical setups

Objective

The aim of Publication IV was to produce a speed map of HLAW of T-joints with attention to weld geometry and propose means for improving the process stability. The experiments were conducted with three optical setups. Beam transfer fibers with core diameters 200 µm, 300 µm and 600 µm were used to vary the dimensions of the focused beam on the surface. 8 mm thick plates of AH36 shipbuilding steel were joined in horizontal position (2F).

Results

The effects of the filler wire feed rate and the beam positioning distance from the joint plane were investigated and the effect of process parameters on the joint geometry was studied based on metallographic cross-sections. Changes of a single process parameter affect the weld geometry considerably. As an example the increase in welding speed usually decreases the penetration and a larger beam diameter usually widens the weld. In addition, it was noticed that the filler material is transferred slightly deeper into the joint, reasons being larger dimensions of the keyhole and different, probably less rapid melt flow in it. Process fibers with smaller core diameters created welds with undercut on the web plate. When penetration was incomplete and the likelihood of porosity occurring therefore higher, it was noticed that welds made by the largest beam had almost no air inclusions and present ones were smaller and quality of the top bead was flawless. This observation contributes towards the conclusion that the process stability is higher when comparable power density of laser beam is distributed to a wider area on the surface.

Contribution to the whole

Publication IV showed that in both, autogenous and hybrid welding, characteristics of the beam determine the geometry of the fusion area, especially the weld width. Increase of filler feed or arc power only widen the top of the bead, the filler wire is not being forced deeper into melt pool if the arc power is increased. However, increase of the diameter of the beam promotes deeper mixing of the filler wire. The keyhole and subsequently melt pool created by wider beams are larger, therefore the solidification time is slightly longer, the melt flow is less rapid and there is more time for the filler material to reach deeper regions of the melt pool.

4.5 Publication V

High power fiber laser welding of single sided T-joint on shipbuilding steel with different processing setups

Objective

Publication V examined autogenous laser welding with three different optical setups to investigate whether full penetration T-joints could be produced with one-sided access to the joint.

Results

In autogenous laser welding of material thickness above 2 mm, obtaining fusion along whole joint during single-sided welding has been a challenge, with the width of the weld being the most prominent limitation. A straightforward way to change the power density on surface of material is to use transfer fibers with different core diameters to change the diameter of the raw beam and therefore the beam parameter product. This maintains the angle in which the beam is entering the keyhole, which is not possible for example when a focusing lens with different focal lengths is used. Experiments were carried out on 8 mm thick AH36 steel. Effects of focal point position, beam incidence angle and beam offset from the flange on the weld geometry were studied in all setups. Based on macrographs of cross-sections, welds with best characteristics were produced using delivery fibers with the largest core diameter. Welds produced with 200 µm and 300 µm process fibers were deep, yet extremely narrow at the deepest section of the joint. Welds produced with a 600 µm process fiber were less prone to undercut formation and had a more uniform shape of the weld toe than welds produced with 200 µm and 300 µm process fibers. From the industrial point of view, the most versatile solution out of the three process fibers tested would be the 600 µm fiber, as it produces wide melt pool at the root of the weld and has wider tolerances to possible displacements of the beam.

Contribution to the whole

In Paper V it was established that the width of the weld is first and foremost determined by the characteristics of the laser beam, e.g. the size of the focused beam. Secondary to beam dimensions is the effect of welding speed, since both of these factors determine the dimensions of the keyhole. Within the Rayleigh length, the power density of the fiber laser beam remains almost constant, therefore wider beams have wider tolerance windows to both, focal point position and lateral positioning of the beam in respect to joint interface. Attempt to validate the Specific Point Energy and Power Factor Model approaches proposed by Suder et. al (Suder & Williams, 2012) for predicting depth and width of the weld was not confirmed in scope of this study. The model is not accurate in case of T-joint, because first of all, heat distribution in joints welded in horizontal position is different from those having vertical axis downwards. Secondly, the claim that "interaction time controls the weld width" applies only for one specific setup with concrete power density of the beam, and only for the width of the weld surface, not the width of the penetration of the weld. It is not possible to achieve the same weld width with welding slower with a beam having a higher power density than the reference case. The model does not apply for larger spot sizes either, but that is because in the calculations it was estimated that the geometry of the spot is rectangular, and with increasing spot size the error of this assumption is accumulating.

5 Conclusions

In this thesis, the effect of process parameters on formation of the weld geometry of T-joints has been studied. In the publications and chapters above, it can be concluded that the high brightness of the fiber laser beam is beneficial for increasing the penetration depth. The main findings are listed as follows:

- Experiments of laser welding of T-joints in 8 mm thick structural steels AH36 and S355MC showed that the use of the IPG YLS-10000 10 kW fiber laser produced to full penetration welds fulfilling the requirements of quality level B (strict requirements) of ISO 13919-1 standard. The comparison of all the experimental data described in publications (Part II) show that the most common weld flaws were lack of fusion at the root (caused by weld missing the joint plane due to narrow weld width), and undercut on the surface of the vertical plate. The occurrence of weld flaws is greatly minimized with use of an optical arrangement with a larger beam diameter.

- In welding with high power fiber laser, the keyhole and melt pool are aligned strictly along the beam axis, which was noticed to be different from welding with CO_2 lasers. Resulting welds have uniform widths throughout the whole depth of penetration. Therefore, the approach angle and positioning of the beam in respect to the joint interface determine the propagation direction of the weld. Consequently, the width of the weld required for producing full fusion without use of filler material should be greater with increasing material thickness.

- The beam size on surface was changed by altering the optical setup by selecting a process fiber with a thicker core. It was found that the weld width is predominantly dependent on diameter and power density of the focused beam, while effects of welding speed or focusing position on weld width are negligible. For welding T-joints, process fiber with core diameter 600 µm was shown to be preferable to 200 µm, as such an optical setup is more robust and has greater positioning tolerances.

- Treating the root of T-joint weld with low power defocused laser beam results in better surface topology of the root side. Applying a sealing run welding is a simple and straightforward way to repair surface irregularities and increase the joint reliability, corrosion resistance and fatigue life under service.

- Using transfer fibers with larger core diameter allows to simplify the manufacturing process in locations where laser-arc hybrid welding is currently used and infrastructure fulfilling laser safety measures exist. HLAW process has a greater productivity and the presence of filler material is beneficial during welding butt joints. However, it is not vital in welding of the T-joint, where one of the plates to be joined is supporting the melt pool. Therefore, welding of T-joints may be carried out on same equipment by LBW, without engaging the arc process. With tenfold smaller heat input than conventional arc processes, welds with complete fusion at the root and convex bead profiles can be produced with single-sided access to the joint.

The above mentioned findings and methods can directly be implemented in production in order to improve throughput and reduce the production costs.

6 Future work

Results of this study show that a high brightness beam with rather large focal spot diameters is capable to weld T-joints with a proper geometry. To contribute to the results of the current work, further investigations could include studies on formation on weld microstructure, analysis of residual strains, and, applying simulation methods for visualising the temperature distribution and predicting the bead geometry. The following topics should be addressed:

- Different weld geometry indicates differences in the melt flow inside the keyhole. Observing the melt flow with high speed camera would lead to a better understanding of process dynamics and provide information for increasing the accuracy of simulation results.

- Detailed investigation of the microstructural composition and mechanical properties of the weld produced by different optical setups. Full penetration T-joints are extremely likely to have high strength properties, but may be rejected during quality control due to hardness exceeding values set in standard. Additionally, hardness of the sealing run welds should be measured. To verify the reliability, extensive mechanical testing should be carried out.

- The stability of the welding process was highest when the optical arrangement delivering a beam with largest diameter was applied. An increase of process stability is likely to be caused by an increased size of the melt pool. Therefore, widening the melt pool by beam oscillation via scanner could produce a similar outcome, given that a suitable oscillation pattern is used. Welding of T-Joints in different welding positions with beam oscillation should be studied.

- Observation of the melt pool dynamics with high speed camera during welding with different optical setups producing identical spot size and using same heat input should be carried out. Keyhole dynamics should be studied using identical spot sizes on the surface resulting from two different optical setups to establish limits of usability of beam defocusing to widen the weld.

- Measuring of t 8/5 cooling rates, residual stresses and strains should be carried out to obtain data about thermal cycles and gaining understanding of structural integrity, fatigue properties of the joints should be studied.

- Joining high-strength and ultra-high-strength steels by laser beam welding without filler material is a wide area for further research. Avoiding problems such as weld softening and preserving the metallurgical properties are of special interest.

- Investigation of keyhole welding with high power diode lasers, so far typically used for cladding, brazing and hardening is becoming relevant. Recent developments in technology of beam shaping elements are likely to offer opportunities for future research in welding in keyhole mode as well.

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Part II: Publications

Publication I

Unt, A., Lappalainen, E., and Salminen, A.

Comparison of welding processes in welding of fillet joints

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Comparison of Welding Processes in Welding of Fillet Joints

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ABSTRACT

T-joint fillet welds are extensively used in manufacturing of marine steel structures like ship decks, bridges, pipes, offshore structures and other heavy machinery. This paper is focused on the welding of low alloy steels AH36 in thickness of 8 mm and S355 in thickness of 10 mm in T-joint configuration using either autogeneous laser welding or hybrid laser arc welding (HLAW) with high power fiber laser. Advantages of modern lasers can be significant especially for shipbuilding preassembly operations. Present article shows and discusses the shape features of one side single pass T-joints made with three different processes: autogeneous laser, gas metal arc and hybrid laser arc welding (HLAW). Factors affecting process stability are systematically researched.

KEY WORDS: Fiber laser; autogeneous laser welding; hybrid laser arc welding; HLAW; MAG welding; fillet joint; low alloy steels; weld quality.

INTRODUCTION

Weight reduction is crucial interest for all industries producing moving masses, as is increasing production efficiency. The possible applications of autogeneous laser welding and hybrid laser arc welding (HLAW) in fields of shipbuilding, transport and aerospace industries are currently extensively researched, since combination of cost-efficient, highly productive process together with fairly mobile and flexible welding equipment have risen high expectations for improved weld quality and economic feasibility (Egerland, 2004, Gerritsen, 2005). Application of new structural solutions such as sandwich panels and use of novel manufacturing processes is first of all driven by economic reasons, but also influenced by safety and tightening ecological standards. Optimization of ship structural elements is one of the main fields where efforts are made (Kozak, 2007). Each vessel contains hundreds of kilometers of welds, more than half of which are fillet welds. Panel fabrication is a bottleneck of ship production, need for post welding straightening-related re-work being not the last reason for this. Using novel materials and manufacturing techniques allow significant cost and material savings through modifications of the structural design.

Laser and HLAW have already been recognized as efficient and reliable joining techniques and viable alternative to conventional arc processes by several shipyards worldwide. Laser welding has higher energy intensity than arc welding processes, having advantages like small weld bead, deep and full penetration and narrower heat affected zone (HAZ). The power density is much higher, although the gross and net heat input is often lower than in arc welding techniques. Steel plates with thicknesses 20-25 mm can be joined in butt joint configuration with welding speed up to 1-2 m/min, which is tens of times faster than conventionally used arc processes (Salminen, 2010). Industrial interest has increased even more after high-power high-brightness lasers such as disk and fiber laser became commercially available. With these laser types, the high power laser welding has become more flexible. Most important feature of fiber lasers and disk lasers is high quality high power beam which can be delivered to workpiece using optical fiber instead of complex system of mirrors, such as in case of CO_2-lasers. Laser welding and HLAW have previously been studied and used industrially with CO_2 and Nd:YAG lasers as main energy sources. However, high power disk and fiber laser-based set-ups made possible manufacturing of structures which were difficult to produce with earlier laser set-ups due to restrictions of accessibility or lack of power.

The wavelength of CO_2 laser ($\lambda \approx 10\,600$ nm) is such that it can only be transferred to workpiece by mirror system, thus accessibility issues have influence on design of components. Beam of solid state lasers ($\lambda \approx 1\,000$ nm) can be transferred to workpiece by optical fiber, meaning possibility to mount processing head on a robot arm more easily and therefore broader flexibility, but maximum output power, limited to 6 kW, was not justifying the initial high cost of laser equipment. High power disk and fiber lasers not having aforementioned power- or beam guidance related problems became industrially available around year 2006. Beam quality is preserved by delivery by optical fiber at all power levels and can be accurately predicted, which increases the reliability of the welding process. Small focal point size and high energy density allow use of filler wire with smaller diameter, which is beneficial when working with complex components that have limitations to workspace because of geometrical features. In addition, wavelength of fiber and disk lasers is in such range that it does not interact so much with shielding gas and metal vapor cloud above the keyhole as beam of CO_2 laser, meaning that process is more stable and weld flaws such as porosity are less likely to appear. Advantages of fiber lasers can be significant especially for shipbuilding preassembly operations, such as welding of sandwich panels and joining structural components, where better accessibility not only shortens the production time, but also reduces the need for re-location of workpieces during different stages of manufacturing and post-welding straightening work.

The requirements for size of the fillet are connected to base metal thickness. Conventionally, the reliability of the fillet weld made between plates oriented 90° apart is evaluated by the size of the fillet, which is determined by multiplying the leg length by 0.707 (Fig. 1).

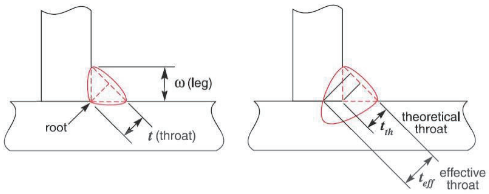

Figure 1. Dimensions of the fillet weld.

In case of arc processes, the throat thickness is determined by measuring the legs of the largest right triangle that is formed within the fillet weld cross-section, not considering the penetration of the weld. However, in case of laser and HLAW processes, the fusion zone between components propagates deep inside on joint groove, creating joint with longer effective throat. This permits reducing the size of external fillet, and, in case of HLAW process, the needed amount of filler material, which allows increasing the welding speed. As a result, direct welding costs are decreased.

Mainly the studies have been addressing the influence of welding speed, laser power and other basic process parameters on weldability, butt joint being typical joint configuration (Weldingh, 2003, Salminen, 2009, Salminen, 2010, Sokolov, 2012). Several researchers have studied HLAW welding of T-joint with CO_2 laser based systems the orientation of the beam and arc in HLAW process and influence of the air gap on processes have been estimated (Fellman, 2004, Yao, 2006, Murakami, 2010). Recent research has investigated the welding of medium thickness T-joints (4 – 8 mm) and eccentric fillet joints made by fiber laser based systems (Alam, 2010, Karlsson, 2011, Cao, 2011).

OBJECTIVE

This paper presents a preliminary study for gathering knowledge about efficiency of the fiber laser based set-up. The used welding position, PA1, is ideal for welding of the fillet joints and most suitable for evaluating the capability of the system. It is well known that this welding position is not possible to be used in most of the industrial applications. The understanding gained about laser and hybrid welding processes will be further used as a reference and a basis for studying other welding positions which are more commonly used in industry.

The aim of the experiments was to study the effect of the line energy and process parameters on the appearance of the weld, depth and shape of the penetration. The effect of laser power, welding speed, beam inclination angle and orientation of the processes in case of HLAW were systematically studied. Finding a parameter window for reaching full penetration was also attempted for both of the thicknesses.

EXPERIMENTAL

Materials

Low alloy steel Ruukki Laser S355MC (EN 10025-2) and ship building steel AB AH36 (ABS) plates were joined in T-joint configuration in PA (1F) welding position using autogeneous laser welding or HLAW processes.

For process comparison also one arc welding experiment was made. The thicknesses and material of the web and the flange were the same. Plates were laser cut to pieces of 350 x 100 mm (length x width) and grid blasted. The filler wire used was ESAB OK AristoRod 12.50 with 1 mm diameter, which is typical filler material for this base material in arc welding. Table 1 shows chemical compositions of test materials and filler wire.

Table 1. Chemical composition of test materials (wt. %)

	C	Si	Mn	P	S
AH36	0.18	0.03	0.7	0.035	0.035
S355MC	0.057	0.02	0.78	0.006	0.004
ESAB OK AristoRod 12.50	0.1	0.9	1.5	-	-
ESAB OK AutRod 12.51	0.1	0.9	1.5	-	-

Process

The autogeneous laser welding and HLAW were carried out with continuous wave (CW) IPG Photonics Yb-fiber laser YLS-10000, with maximum power output 10 kW, as laser power source and Kemppi ProMig 530 as arc power source. The welding head used was Kugler LK190 mirror optics laser welding head with Binzel MAG torch. Approximate focal point diameter of the laser beam was 0.56 mm, resulting from 300 mm focal lens, 125 mm collimation lens and ø 200 µm process fiber. Only pulsed arc was used, synergy setting was constantly on, thus arc current and voltage were varied in accordance with feeding speed of filler wire. In HLAW tests Ar + 5% CO_2 was used as shielding gas and delivered to the work piece with the arc torch. In laser welding experiments shielding gas was not used, but small air knife of compressed air above the keyhole was being used for cutting the metal vapor cloud.

Prior to welding the steel plates were tack welded together in a form of inverted T. The length of the weld was 165 mm. Constant parameters were tilt angle of the arc welding torch, 45 degrees, travel angle of the arc torch, 58 degrees, process distance 3 mm and free wire length 15 mm. Process variables are shown in Table 2. Experimental set-up of laser welding experiments is shown on Fig. 2 and for HLAW on Fig. 3.

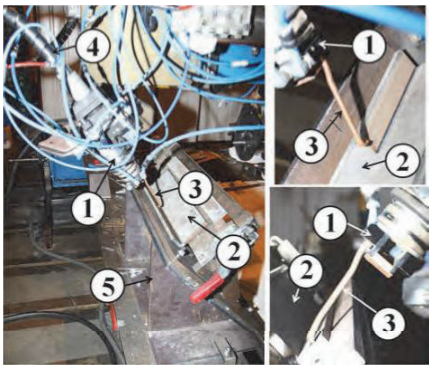

Figure 2. Experimental set-up of laser welding experiments. 1 = laser welding head, 2 = workpiece, 3 = compressed air nozzle, 4 = process fiber, 5 = fixing system.

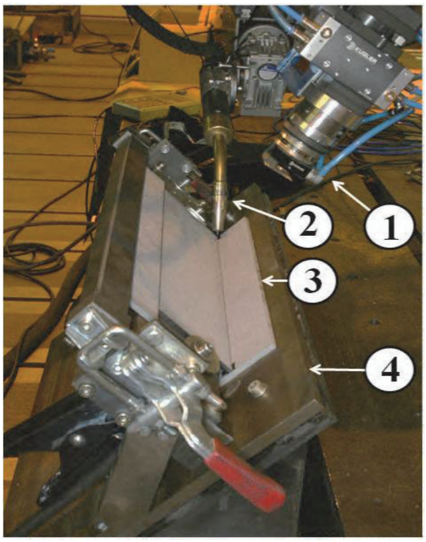

Figure 3. Experimental set-up for HLAW welding experiments. 1 = laser welding head, 2 = MAG welding torch, 3 = workpiece, 4 = fixing system.

Table 2. Experimental set-ups and parameters. Beam incidence angle is angle between flange plate and laser beam perpendicular to travel direction. Beam position is offset measured from flange plate to the direction of web plate in the surface of the plates. Arc position means the horizontal offset of the wire related to corner of the joint in top surface, 0 is in the middle of the joint.

Material	8 mm AH36	10 mm S355MC
Process used	Arc, Laser, HLAW	Laser, HLAW
Laser power (kW)	4.56; 5; 5.56; 6	5.56; 6; 8; 8.4; 9; 9.5
Focal point position (mm)	+2, -2	-2
Welding speed (m/min)	0.5 – 2.5	0.75 – 2.5
Beam incidence angle (°)	6	6
Leading process	Laser	Laser, Arc
Beam position (mm)	0, 0.5	0.2, 0.5, 0.8
Arc position (mm)	0	0, 1, 2

The experiments were carried out at various energy inputs (i.e. different combinations of laser power and welding speed) on 8 mm thick AH36 steel and 10 mm thick S355MC steel. Aim was to obtain full penetration with acceptable weld quality with both processes studied. In preliminary experiments air gap of 0.5 mm was used to see its influence on penetration depth and for simulating possible fit-up mistake likely to occur in industrial sites. Air gap was created by placing steel strips between the plates at the start and end of each weld.

For comparison, one arc weld with industrial robot was made on 8 mm thick AH36 steel, using Kemppi KempArc Pulse 450 and ESAB OK Autrod 12.51 filler wire (Ø = 1 mm). Welding speed was 0.54 m/min and filler wire feed rate 12.6 m/min, torch angle 45°. Optimal and most efficient welding parameters were not searched for, the aim was to obtain joint with fillet size comparable to laser and HLAW processes. In this paper productivity of the processes is not addressed.

Test methods

After welding, visual evaluation of top and root surfaces of weld bead was carried out for all of the welds to examine the overall appearance of the welded samples for qualitative assessment. All welds were visually evaluated for commonly occurring weld imperfections described in EN ISO 13919-1 standard. Special attention was paid for imperfections like undercuts, excessive penetration and lack of penetration because of their possible effect on the fatigue properties of the weld, acting as a notch for crack initiation.

Further, welds having smooth and even top and root sides without obvious defects such as excessive spatter were sectioned transverse to the welding direction. Macrographs were taken from polished and etched specimens for inspection of penetration, dimensions and shape of the fusion and heat affected zones.

Fracture tests were made for selected welds having good visual appearance. The sample was folded over the weld side of the fillet until it folded flat upon itself or failure occurred. Fracture surfaces of ruptured test specimens were evaluated to check the weld for soundness and imperfections.

Correlation between consumed energy and weld performance were investigated, hybrid laser arc weld and arc weld having comparable total line energy were compared. Line energy of laser and hybrid laser arc welds was calculated based on the equations (1) and (2),

$$E_{laser} = P_L / v_w \quad (1)$$

$$E_T = E_{arc} + E_{laser} = (U \cdot I \cdot 60) / v_w + (P_L \cdot 60) / v_w \quad (2)$$

Where

E_{laser} - energy of laser welding [kJ/mm],
P_L - laser output power [kW],
v_w - welding speed [m/min],
E_T - energy of laser-arc hybrid welding [kJ/mm],
E_{arc} - energy of arc welding [kJ/mm],
U - voltage of arc [V],
I - current of arc [A].

Hardness curves were obtained for arc, laser and laser-arc hybrid welds produced with similar line energies. Vickers hardness tests with 5 kg load were carried out using Struers DuraScan hardness measuring equipment. Distance between indentations was 0.4 mm; measuring lines were positioned at 1 mm from surface of top bead across the weld from base material to base material in direction of the weld bead. For wider welds, arc weld and HLAW weld whole width of the melt area was not measured, only 4 indentations from both fusion lines.

RESULTS AND DISCUSSION

Basic parameter study

During preliminary experiments, it was found that focal point position 2 mm below the top surface of the specimen was optimal for obtaining weld beads with acceptable visual appearance. It was also noted, that influence of pre-adjusted 0.5 mm air gap was insignificant, since air gap decreased during welding process from given 0.5 mm to near 0 mm, so that actual size of the gap between the plates was difficult to define. Because of this, in secondary experiments all laser welding experiments in both thicknesses and HLAW tests in 10 mm thickness were made without pre-adjusted air gap. Fig. 4 shows how focal point position is influencing the shape of the weld cross section.

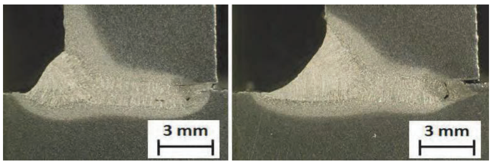

Figure 4. Focal point position: left +2 mm, right -2 mm. AH36 8 mm, welding speed 1 m/min, filler wire feed rate 5.2 m/min, laser power 4.56 kW. Arc power: left 3.15 kW, right 2.34 kW.

From the Fig. 4 it can be noticed how the top bead of the weld becomes wider, smoother and more uniform when focal point position is lowered from +2 mm to -2 mm. Penetration depth stays at the same level. Not similar arc power might also have influence of shape of the weld. Reason for different arc powers is unknown.

Further, the effect of the beam position i.e. distance from flange was studied. Fig. 5 displays cross-sections of welds made in 10 mm S355 using laser leading configuration, laser power 8 kW, welding speed 0.75 m/min, filler wire feed rate 7.2 m/min and focal point position -2 mm.

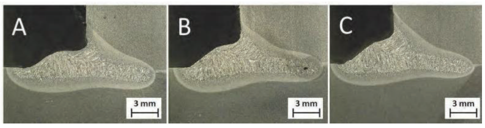

Figure 5. Welding of 10 mm S355. Effect of beam position on the web. The distance from joint and flange upwards on the web: A: 0.2 mm, B: 0.5 mm, C: 0.8 mm.

It was noticed, that increasing the distance from the flange helped to avoid formation of the minor undercut at the web plate and reduce sinking of the weld. The penetration was deepest at 0.8 mm offset, when widest area of the joint was exposed to the beam, as depth of the fusion zone in HLAW was always propagating in direction of laser inclination angle.

For determining the effect of laser power on penetration, experiments with varying power levels were made while other process parameters were kept constant: welding speed 1 m/min, filler wire feed rate 5.2 m/min, focal point position – 2 mm. Fig. 6 shows how the shape of the weld changes in HLAW when laser power is increased.

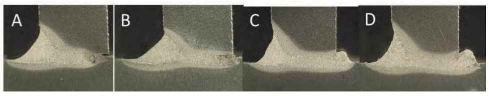

Figure 6. Welds in 8 mm AH36. Effect of laser power.
Laser power: A: 4.56 kW, B: 5.0 kW, C: 5.56 kW, D: 6.0 kW.
Arc power A: 2.34 kW; B: 2.26 kW, C: 2.24 kW, D: 2.20 kW.

As can be seen from Fig. 6, increasing laser power leads to higher width to depth ratio of the weld. The laser power needed for full penetration and complete fusion at the root side of the weld is 5.56 kW (Fig. 6 c). The width of the joint does not change in area where arc does not reach, which means that some of the extra laser power is absorbed near the surface and used for unifying the heat flow and shape of the top bead. Examples show that laser energy determines the depth of penetration, while arc energy is consumed close to surface on melting of the filler wire and preheating the melting pool for the beam. At further increase of laser power the melt generated is being pushed through the weld. Lack of penetration at insufficient power levels or the sharp juncture forming from solidified melt between the web and flange at too high power should both be avoided, as both might act as stress concentration points under loading.

Effect of orientation of the processes in HLAW

It is known that orientation of welding processes in HLAW (whether the leading process is arc or laser) has influence on properties of joint. Fig. 7 shows typical features of either orientation.

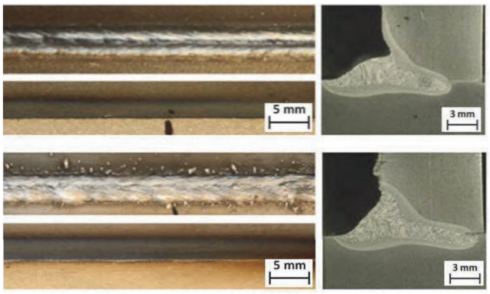

Figure 7. Hybrid laser arc welding of 10 mm thick steel. Laser angle 10 degrees. Laser leading configuration (up) and arc leading configuration (down). Top, root and cross-section. Laser power 9.5 kW, welding speed 1,25 m/min, laser power 9.5 kW, focal point position -2 mm, filler wire feed rate 8,2 m/min.

As can be seen on Fig. 7, arc leading configuration produced deeper welds with more even shape than laser leading configuration. Uneven surface of weld bead and small undercuts (less than 1 mm) were rather common with laser leading configuration, while arc leading technique produced weld bead with smoother surface quality under same parameters. In arc leading configuration more spatters in top side of the weld can be noticed. When arc is the leading process penetration is deeper and welds have less porosity.

Comparison of welding processes

In order to analyze the welding processes, it was decided to compare the geometrical features, hardness profiles and relationship between the heat input and penetration. Fig. 8 presents joints made with comparable line energy with three processes (arc weld 766 J/mm, hybrid laser arc weld 785 J/mm and laser weld 600 J/mm). The welding speeds were 0.54 m/min in arc welding and 0.5 m/min in HLAW and laser welding.

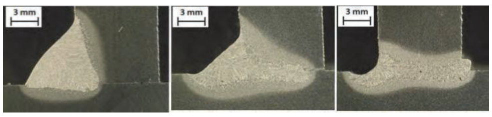

Figure 8. Cross-sections of left: arc weld, middle: hybrid laser arc weld and right: laser weld made with comparable line energy.

Fusion zone, heat affected zone and base metal are clearly distinguishable. In arc welding the joint is made with filler material, in laser welding it is formed from molten base material. HLAW is a combination of those, resulting in larger weld cross section area (HAZ + melt area) than in case of arc or laser processes alone. However, the full penetration achieved with laser welding is decreased to partial penetration when changing to HLAW process. Different sizes of the fusion area are resulting from character of heat distribution in the different welding methods. Arc weld has the largest melt area (29.4 mm^2), mainly consisting of molten filler wire, followed by HLAW weld (24.5 mm^2) and autogeneous laser weld (19.0 mm^2). Fig. 9 shows hardness profiles of the welds displayed in Fig. 8.

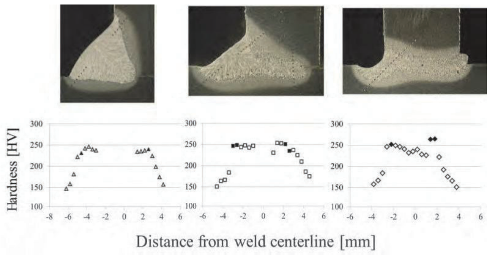

Figure 9. Hardness profiles of weld top beads. Indentations in intersection of HAZ and melt area are marked as filled.

In all welds hardness increases gradually as approaching the fusion zone and slightly decreases in weld zone. Highest hardness values are near the fusion line. Traditionally, laser welds are criticized for having too high hardness for being approved by the quality standards made for the arc welding. From Fig. 9 it can be seen, that hardness profiles for three welds under review are not that different. Maximum hardness values remain near 250 HV in all of them. Despite laser weld having about 150 J/mm lower line energy, full penetration was achieved while the hardness remained at same level with arc and HLAW produced welds. It should be remembered, that finding the highest hardness values of the weld was not purpose of this experiment. The hardness was measured only from the top of the weld, the highest hardness values are in other regions of the weld. Evaluating the welding processes by highest hardness values should be in further studies.

Experiments showed that full penetration in 8 mm thick steel was reached with both, HLAW and autogeneous laser welding process at power levels higher than 6 kW. Fig. 10 shows typical features of either technique. Welds are made with 6 kW laser power at welding speeds 1 m/min, 1.75 m/min and 2.25 m/min. Constant parameters were: focal point position -2 mm and beam position 0.5 mm. In case of hybrid welding arc power was 2.24 kW at 1m/min, 3.34 kW at 1.75 m/min and 4.15 kW at 2.25 m/min.

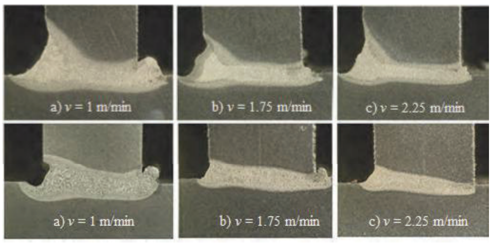

Figure 10. Welding of 8 mm AH36 with HLAW (up) and autogeneous laser welding (down).

As can be seen from Fig. 10, increase of welding speed causes narrowing of the weld bead, while penetration depth does not decrease significantly. In case of HLAW the fusion zone is larger at lower speeds as more base material is melted. In HLAW, the shape of the fillet is not straightforwardly correlated to welding speed, since welds with acceptable quality are made in certain lower speeds and certain higher speeds. Top bead is smooth at welding speed 1 m/min, but becomes irregular at 1.75 m/min. Upon increasing welding speed, the bead width decreases while surface becomes smooth again. In laser welding, on the other hand, low welding speed leads to sagging of the weld, and optimal speeds are above 1 m/min. Welding in horizontal position might be more tolerant to this. In case of laser welding, there is straightforward relation between the quality and width of the weld and welding speed. The increasing of the speed is also directly correlated to the penetration depth, but in HLAW the once achieved full penetration stays longer when speed is increased. Minor lack of fusion at the root side was occurring at high speeds with both processes at 2.25 m/min, however in bridgeability of HLAW process is better and parameter window for joints with acceptable quality is larger.

Fig. 11 shows the penetration depths and actual throat sizes measured from macrographs of 8 mm HLAW welds. All experiments displayed are made with laser power either 5.56 kW or 6 kW, the welding speed was varied in range of 0.75 m/min to 2.5 m/min. In some cases the actual length of the fillet is longer than thickness of material, 8 mm, as length of the actual throat takes in account both, depth of full penetration and size of external fillet.

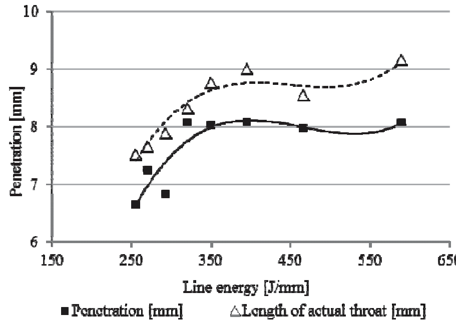

Figure 11. The dependence of the weld penetration and actual throat from the total line energy in 8 mm thickness joints.

Sound welds with good surface quality were also made in 10 mm thickness regardless of not achieving full penetration. Fig. 12 shows hybrid weld and laser weld having deepest penetrations in 10 mm thickness.

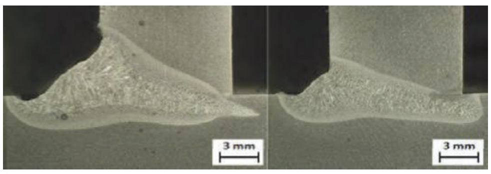

Figure 12. HLAW weld (left): arc leading configuration, laser power 9.5 kW, welding speed 0.75 m/min, filler wire feed rate 9.5 m/min; Laser weld (right): laser power 9.5 kW, welding speed 1 m/min.

The lack of fusion is 1.3 mm in HLAW weld and 2.4 mm in laser weld. In both cases the laser power was sufficient to create full penetration, but weld is missing the centerline of the joint and propagating in direction of beam incidence angle. The beam position was 0.5 mm in both cases. Increase of this position, and/or increase of the beam alignment angle might result in full penetration welds with good quality using HLAW process. Concerning laser welding, obtaining full penetration by manipulation of beam angle or position is also possible, but more complicated and sensitive to adjustment. The parameter window is much smaller, since joint is formed from the base material only and defects like undercut or drop-through of the weld are likely. Relation of penetration and actual throat length to line energy for 10 mm thick S355 is presented in Fig. 13.

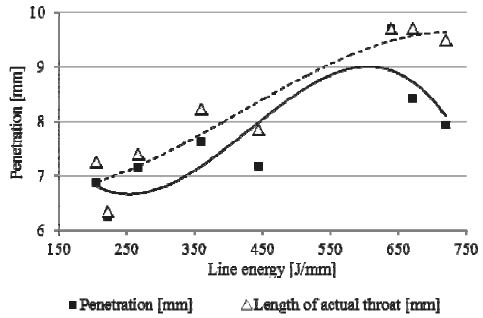

Figure 13. The dependence of the weld penetration and actual throat from the total line energy in 10 mm thickness HLAW joints.

Fig. 11 and Fig. 13 show that increasing line energy results in increase of the length of the actual throat and this length can be predicted easily. The length of actual throat is increasing because top bead is growing when welding at slower speed and higher power with sufficient amount of filler material available. Line energy influences the weld shape formation; increasing welding speed decreases the volume of melted material and solidification speed. The penetration depth (measured from the edge of the web to the end of the fusion zone inside of the joint) does not have such straightforward connection to line energy, as in cases under review the obstacle limiting penetration was the incline angle of the beam. In case of 8 mm thickness, proportion of the penetration depth from the length of actual throat seems to stay almost constant in all line energy levels. In 10 mm thickness this cannot be noticed.

Fracture tests

Fracture tests were performed on joints considered the best in visual evaluation. The specimens were placed top bead down on the testing machine and force was applied on the sample from root side until the weld ruptured or flange folded over the web. 12 samples, 8 hybrid and 4 laser welds were tested. The complete failure of breaking in two pieces occurred only in one hybrid weld (not having full penetration and made with laser leading configuration). In spite of lack of penetration in some samples subjected to testing, the welds were torn open, but not completely, plates did not detach from one another. Fig. 14 shows two of the tested HLAW welds in 10 mm plate thickness. The width of the section subjected to bending is 30 mm; view is from root side of the weld.

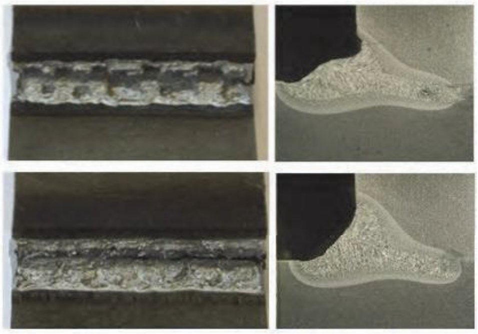

Figure 14. Fracture test results in two HLAW welds with partial penetration in 10 mm plate thickness, view from root side. Up: Laser leading configuration, laser power 8 kW, arc power 2.3 kW, welding speed 0.75 m/min, filler wire speed 7.2 m/min; Down: Arc leading configuration, laser power 9.5 kW, arc power 2.5 kW, welding speed 1 m/min, filler wire speed 6.5 m/min. On the left are the samples after fracture testing.

Examination of the fracture faces revealed porosity throughout the upper weld, while in weld shown in lower image porosity is hardly detectable, fusion area is much more even. Fig. 15 shows fracture test results of two full penetration laser welds in 8 mm thick AH36 steel.

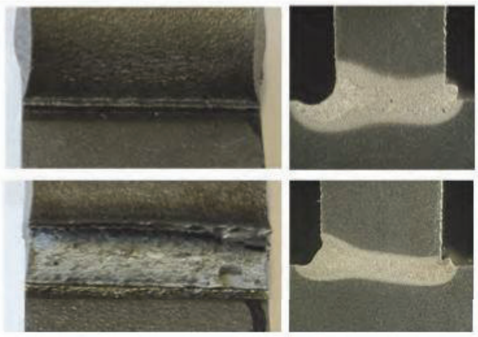

Figure 15. Fracture tested flat folded full penetration laser welds, view from root side. Up: Laser power 5 kW, welding speed 0.5 m/min, line energy 600 J/mm; Down: Laser power 6 kW, welding speed 1.25 m/min, line energy 206 J/mm. On the left are the samples after fracture testing.

Regardless of lower points in visual evaluation and minor undercut, weld presented in Fig. 15 Up did not rupture at all when pressed flat under load. This is perhaps because energy input per unit length was larger. In lower weld fracture occurred in fusion line, thus weld made with lower line energy is more brittle and can be predicted to have higher hardness. The relationship between line energy and fracture behavior under load is a subject to further studies.

CONCLUSIONS

It is possible to obtain good quality full penetration welds with both, laser and hybrid laser arc processes in 8 mm thickness. In 10 mm thickness sound welds were produced, but full penetration was not achieved, but is very likely if the angle of laser incline is increased.

When comparing the penetration depth in laser welding and HLAW, laser welding produces full penetration more easily at higher welding speed, but has narrower parameter window of acceptable joint quality than HLAW. In both thicknesses and both materials studied, at same process parameters, arc leading orientation produced welds with better quality than laser leading configuration, in which defects like undercuts and porosity were appearing.

The hardness profiles of all three processes made with similar line energy showed that hardness values are at the same level regardless of the process. Additionally, weld made by laser process was only one with full penetration. It should be also noted that in fracture testing the same weld was the only one which remained unbroken when folded flat upon itself. Still, concerning hardness values it should be mentioned that values obtained are measured near the top bead of the weld for comparison of the processes, not for finding the highest hardness values of each process.

Laser welding of AH36 with 10 kW fiber laser system produces strong welds with maximum hardness. In HLAW the volume of the molten material is larger, cooling is slower and hardness of the weld and HAZ is less.

Fracture test results show that the fracture occurred along the interface between the heat affected zone and the base material, where the hardness reaches highest values.

In both of the tested processes, laser welding and HLAW there are many parameters influencing the shape of the weld cross section, these parameters also act together. Predicting the influence of a single parameter can be difficult as even minor changes have influence on the outcome. Nevertheless, deeper penetration and fewer distortions at same energy level show that laser welding and HLAW have advantages over traditional arc welding processes

Further studies are needed to apply these processes to other welding positions. This present paper summarizes principal knowledge of the processes and their efficiency achievable with used equipment in the most efficient welding position for fillet welding.

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Publication II

Unt, A., Poutiainen, I., and Salminen, A.

Effects of sealing run welding with defocused laser beam on the quality of T-joint fillet weld

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Effects of sealing run welding with defocused laser beam on the quality of T-joint fillet weld

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Abstract

Fillet weld is the predominant weld type used for connecting different elements e.g. in shipbuilding, offshore and bridge structures. One of prevalent research questions is the structural integrity of the welded joint. Post weld improvement techniques are being actively researched, as high stress areas like an incomplete penetration on the root side or fluctuations in penetration depth cannot be avoided. Development of laser and laser-arc hybrid welding processes have greatly contributed to increase of production capacity and reduction of heat-induced distortions by producing single pass full penetration welds in thin- and medium thickness structural steel parts. Present study addresses the issue of how to improve the quality of the fillet welds by welding the sealing run on the root side with defocused laser beam. Welds having incomplete or excessive penetration were produced with several beam angles and laser beam spot sizes on surface. As a conclusion, significant decrease or even complete elimination of the seam irregularities, which act as the failure starting points during service, is achieved.

Peer-review under responsibility of the Bayerisches Laserzentrum GmbH

Keywords: laser welding; weld quality; sealing run welding; fatigue life

1. Introduction

Laser welding and hybrid-laser-arc-welding (HLAW) are being more and more applied in ship-building, steel working and metal construction industries, being preferred for small heat input, higher quality and speed up the production. Replacing traditional GMAW welding with these processes allows more efficient production and energy saving by weight reduction, for example to weld stiffeners to thinner ship decks. One of the reasons that held back

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the application of thinner metal sheets in steel construction is the damage caused by excessive heat input of traditional welding processes. Heat induced distortions are time-consuming and expensive to correct and limit the use of steel plates with thickness under 8 mm (at least) in ship building industry. Defects like underfill or excessive penetration cannot fully be avoided due to the structure of fillet joint. The combination of welding residual stresses with operating stresses to which engineering structures and components are subjected can promote failure by fatigue. Unrepaired distortion is also causing stress increase when compared to nominal stress level. However, autogenous laser welding and laser-arc hybrid welding are high efficiency processes producing narrow deep joints with smaller thermal distortions and are less prone for above-mentioned faults. Both processes are flexible, easily automatable and adaptable to manufacturing conditions in workshop or in field. Fillet welding with laser can be performed with various different techniques, autogenously and as a combination with arc welding processes as shown by Unt, et al. (2013). It has been shown that hybrid laser welding is also suitable for fillet joint welding in case of aluminum by Wang Tao, et al (2013) and Mazar Atabaki, et al., (2014). Adding filler wire into laser welding process has been successfully introduced also in case of multipass welding to improve the maximum achievable penetration with certain laser power by Elmesalamy, et al., (2014). Adding the filler wire will increase the number of parameters considerably as observed in studies of Syed & Li, (2005) and Salminen (2010).

Fillet weld is most common type of the joint in shipbuilding, energy and automotive industries (Deng, et al., 2007). The joints made with laser welding and HLAW have smaller throat thickness and leg length than those made with GMAW, and deeper penetration, usually joining the two components fully throughout. In exploitation, the most stress sensitive places are discontinuities as undercuts or overlaps and sharp junction at the root side of the joint. Even with B class surface quality (EN ISO 12932:2013), the root of the weld might have problems such as melt flow through or minor lack of penetration that create geometry that acts as a notch when subjected to bending or impact forces.

E.g. ship deck structures are typical example of this kind of T-joint where the attachment acts as non-load carrying stiffener. In fatigue respect these details are usually welded on both sides. In the fatigue assessment of non-load carrying stiffener the flange is loaded with tension or out-of plane bending. This results that the fatigue crack will propagate from weld toe to the deck plate. Fatigue behavior is this way governed by the quality of the weld toe in the deck side. One sided fillet weld is not normally recommended since the lack of penetration results a sharp crack like imperfection. In the IIW fatigue recommendations (Hobbacher, 2007) the fatigue class for the as welded non–load carrying fillet weld is FAT 80 based on the nominal stress. For the root side the fatigue class drops down to FAT 71. In fatigue life this corresponds to 30% decrease. HLAW can reach a full penetration but the root is still in many cases prone to fatigue. Root side is difficult to control and thus weld root can have a sharp geometrical transition to loaded plate.

Transition to use thinner materials is usually achieved by a new design or use of higher strength steels. This will lead to a complex structure or directly to higher stresses. In both cases, structures under fluctuating load will be more sensitive to fatigue failure. To overcome this, closer attention must be paid to stress analysis and quality of welds.

Fatigue strength can be improved using several methods. Methods are used to shape weld toe geometry, remove initial cracks and possible introduce a compressive stresses (Haagensen, 2003). TIG dressing has similar improvement mechanism than a laser melting. Both methods melt the weld toe area, shaping it and removing possible initial cracks. Although re-melting can introduce new initial cracks, the heat input is smaller and the size of the initial cracks can be smaller. The IIW recommendation gives for the TIG dressing method a 1.5 improvement in fatigues strength, maximum strength set as FAT100. This way the fatigue strength of the root can be increased to equal or even higher than toe weld toe side.

The most of the improvement is gained with the large toe radius (Nykänen, et al., 2007). The weld flank angle has less importance if the toe radius is large. The resistance to fatigue is assessed in this study by visual inspection of the toe radius and overall quality of the weld-base metal transition.

The purpose of this study is to examine the techniques for improving the quality of the fillet welds by welding sealing run to the root side with laser beam i.e. weld another small weld on the root side after welding to smoothen the weld toe and ensure better overall quality of weld root. As a basis of evaluation of weld geometrical properties, a welding speed map was created welding 8 mm thick structural steel plates in T-joint configuration autogenously with 10 kW fiber laser, then welds were subjected to sealing run welding with laser beam outside of the focal plane. The shape and hardness of the joints was investigated, as the effect of sealing run on the soundness of the joint.

2. Experimental procedures

Ship building steel AB AH36 (ABS) plates 8 mm in thickness were joined in T-joint configuration in horizontal welding position (2F). Prior to welding, plates were tack welded together in the form of an inverted T. The experimental set-up used for the experiments is shown on Fig. 1.

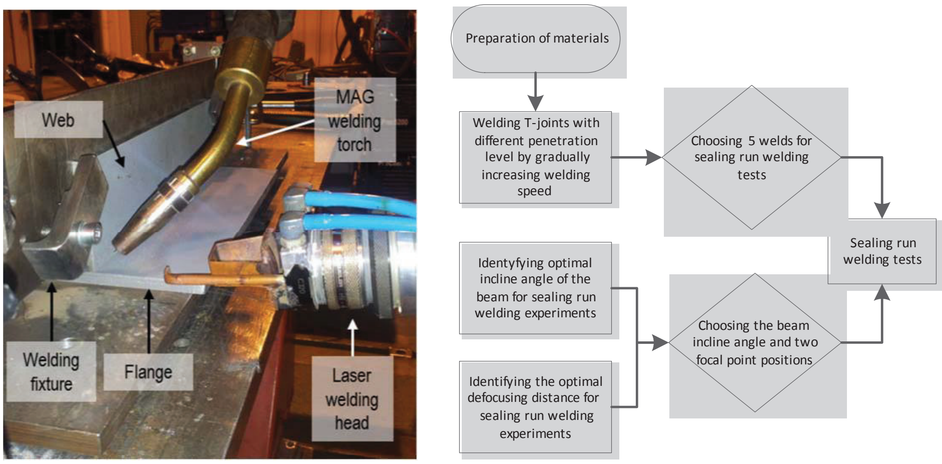

Fig. 1. Left: experimental set-up used (MAG torch was not used in these experiments); right: the flowchart of experimental procedure.

The IPG YLS-10000 continuous wave fiber laser having wavelength 1070 nm with maximum power output 10 kW was used with Kugler LK190 full mirror optics laser welding head. Focal point diameter of the laser beam was 0.56 mm, resulting from 300 mm focusing lens, 125 mm collimation lens and ø 200 µm process fiber. The shielding gas was not used. The length of each weld was 165 mm.

2.1. Preparing the welds

First step of the experiments was creating welds with different root geometries and various degrees of penetration. For this, joints were produced with nine different welding speeds while keeping other process variables constant. The welding parameters used are shown in Table 1.

Table 1. Parameters used for preparing the welds for further root sealing experiments.

Parameter	Value
Laser power (kW)	6
Welding speed (m/min)	0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5
Defocus (mm)	-2
Beam angle from flange (°)	6

Joints having various degrees of penetration and weld root shapes were produced, and subsequently used as test specimens for the sealing run welding tests. The quality of the welds was evaluated based on ISO 13919-1 standard and categorized into three quality levels: B - stringent, C - intermediate, D - moderate (ISO 13919-1, 1996).

2.2. Experiments with defocused laser beam

Second step in experimental was determining the most useful parameters for the sealing run welding for treatment of the root sides of the welds produced in first step. The traverse speed of the beam and laser power were kept constant at 1.5 m/min in both of the test series. The centerline of the beam was kept at the junction of web and flange. The effects of focal point distance from the surface of the workpiece i.e. the effect of laser beam spot size on workpiece surface was studied together with the effect of the inclination angle of the laser beam. The test variables are explained in Fig. 2 and used parameters are shown in Table 2.

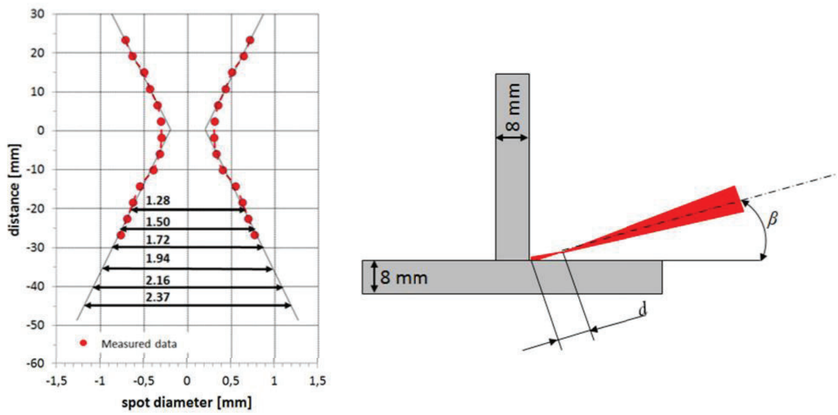

Fig. 2. Left: the beam diameters at focal point distances used in this study; right: focal point distance *d* and beam angle *β* from the flange.

Table 2. Parameters used for determining best possible melting values

Parameter	Value
Laser power (kW)	3
Welding speed (m/min)	1.5
Focal point position (fpp), *d* (mm)	20, 25, 30, 35, 40, 45
Beam angle from flange , *β* (°)	6, 10, 15, 22.5, 30, 37.5, 45, 50

2.3. Sealing run welding tests

After examining the cross-sections produced by larger laser spot on surface, the root sides of five chosen welds were treated using beam with high focal point position. These welds were selected based on visual appearance of the root side in as-welded state, ranging from large amount of melt at low welding speed (0.5 m/min) to no melt at all at highest welding speed tested (2.5 m/min). Root side of each weld was tested with two different beam intensities selected according to previous experiments. Experimental parameters are shown in Table 3 below.

Table 3. Process parameters and variables in the sealing run welding tests

Parameter	Value
Laser power for welding (kW)	6
Laser power for sealing run (kW)	3
Welding speed (m/min)	0.5, 1.0, 1.5, 2.0, 2,5
Welding speed sealing run (m/min)	1.5
Focal point position (fpp) (mm)	25, 40
Beam angle from flange (°)	6 (welding), 45 (sealing run)

Afterwards, three cross-sections were selected from each weld: one from part of the weld in as fillet welded state and two from sections with sealing run welded, respectively. Samples were polished and etched using Nital solution (a 2% mixture of ethanol and nitric acid), macrographs of the weld cross sections were taken for inspection of penetration, defects, dimensions and shape of the fusion and heat affected zones.

Vickers hardness (HV5) was measured from the fusion lines of all the welds to determine the highest values in each weld; also the fusion zone was tested. The hardness of the sealing run welds was also measured, to evaluate whether there is an increase after secondary run. Four indentations were made in top, root and middle of the weld, and the values of each measuring position were averaged. Hardness of sealing run welds on the root side was also measured along newly formed fusion lines of the melt zone.

3. Results and discussion

3.1. Joint morphology and shape

First of all, T-joints were produced autogenously by laser, keeping identical conditions for all other parameters except the welding speed, which was increased from 0.5 m/min to 2.5 m/min at 0.25 m/min steps.

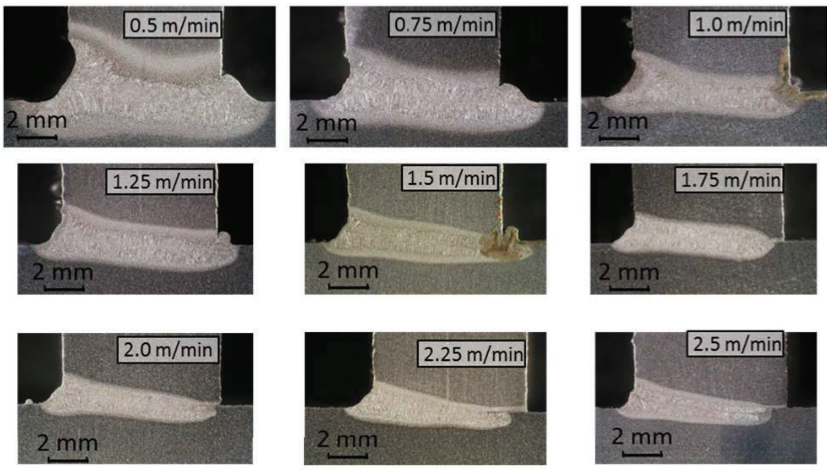

Fig. 3. Cross sections of the joints welded with 6 kW laser power, defocus -2 mm and welding speeds ranging from 0.5 m/min to 2.5 m/min.

Macrographs of cross-sections were taken for each welding speed covered. Fig. 3 shows the changes of the weld shape and depth of penetration as welding speed is increased. As a result of this test series, welds with excessive penetration (0.5 and 1 m/min), full penetration (1 and 1.25 m/min) and various degrees of lack of penetration were produced (1.5 – 2.5 m/min). All of the produced welds were free of most commonly occurring welding defects such as spatter, cracks, porosity or undercuts.

As Fig. 3 shows, welding speeds less than 1.5 m/min produce fully penetrated joints having excessive melt at the root side, which gradually decreases as the welding speed is increased. At 1.5 m/min, the joint is beginning to lose its soundness, as the melt in the root side is not continuous throughout whole weld, but, rather occurring as droplets. When the welding speed is more than 1.5 m/min, the underfill can be seen and the web and flange are separated at the root. The area of the fusion and heat affected zones is shrinking as welding speed is increasing, at 1.5 m/min, the full penetration is lost, as energy input is not sufficient. Minor amount of melt can be observed pushing through and creating minor root occasionally forming metal pearls on root side and occasional lack of penetration. This phenomena is well known also in case of butt joint where slightly low energy input is forming, due to instable keyhole, similar root (Salminen, et. al 2010) At welding speeds above 1.75 m/min there is evident lack of penetration, however the joints produced are free of any other welding defects.

Welding speeds 0.5 m/min and 0.75 m/min in Fig. 2 shows a full penetration with good weld toe geometry in the root side. On the stiffener side weld toe there is a sharp transition, but in the 0.5 m/min speed it is far from the lateral plate that it is not necessarily critical. With the 0.75 m/min speed the weld toe is so close to the loaded plate that fatigue crack might start to grow from there. Except for the slowest speed root side requires a post-weld treatment to improve the fatigue behaviour of the detail.

3.2. Effect of welding speed on penetration depth and hardness of the welds

From the results of Vickers hardness test at 1 mm depth from the face and root and from the middle of the specimen, it was found that there were only small differences between all measuring points, suggesting that transformation to martensite during cooling was happening at similar rate. Additional re-melting of the root side during the sealing run welding did not change the hardness regardless whether the root side originally had an excessive melt or lack of thereof. The results of hardness test are summarized in Fig. 4.

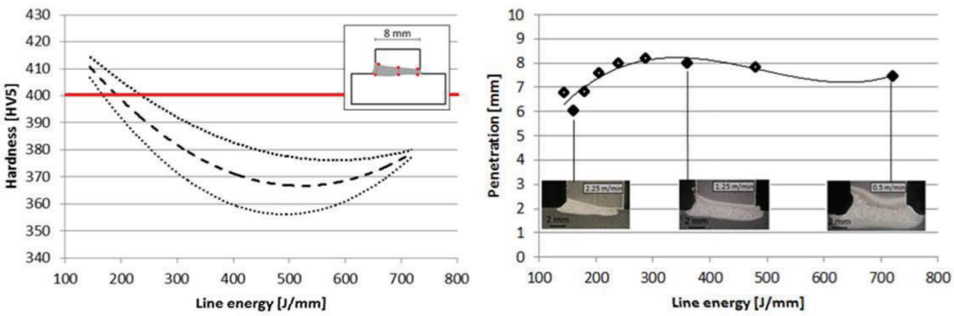

Fig. 4. Left – the averaged hardness of the fusion lines +/- 5% (red line marking the upper acceptable limit); right – the penetration dependence on line energy.

The hardness in the fusion lines of all the welds and was ranging from 360 to 410 HV5, all welds with exception of one made with welding speed 2.5 m/min fulfil the criteria stated in Classification Society guidelines for laser welding in shipbuilding (Lloyd's Register of Shipping, 1996) having hardness below 400 HV5 (shown by red line in Fig. 4 left). The hardness of weld zone was alike in all of the welds, fluctuating around 350 HV5. From Fig. 4 right, it can be seen that the line energy mainly has effect on the dimensions of the weld and heat affected zone. T-joints welded with higher speed have very narrow fusion zone (less than 1 mm wide at the end), and while there may be enough power available to melt the steel to 7 mm depth, the slight misalignment of the beam along the joint might cause a loss of penetration, as weld made with 2.25 m/min shown in Fig. 4 right demonstrates.

3.3. Effect of beam defocusing and variation of the beam incline angle

Fig. 5 shows the shape changes when focal point position is being increased. The diameter of focused beam is ~ 0.6 mm, expanding to ~ 2 mm at focal point position of 20 mm, which was chosen to be the starting point for sealing run welding experiments.

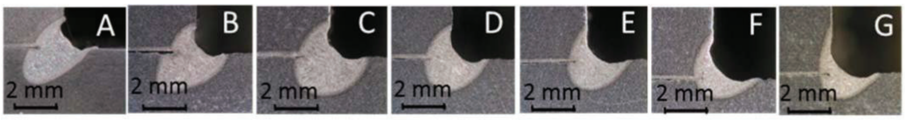

Fig. 5. The cross-sections of the tracks formed while gradually shifting focal point position. Laser power 3 kW, beam angle 45°, welding speed 1.5 m/min. Focal point distance: A -20, B-25, C-30, D-35, E-40, F-45, G-50 mm.

From Fig. 5 can be seen the effect of focal point position or actually the spot size on surface on the weld cross-section. The weld toe radius increases when the focus distance is getting longer, simultaneously with the long focal point distance the penetration is decreased. In Fig. 5 A and B the intensity of the laser beam seems to be high enough to form a keyhole. From D to E the process is more similar to conduction mode laser welding, and in F and G energy density is even lower, forming a shallow and wide weld nugget. Fig. 6 shows the effect of the beam incline angle on shape and size of the weld.

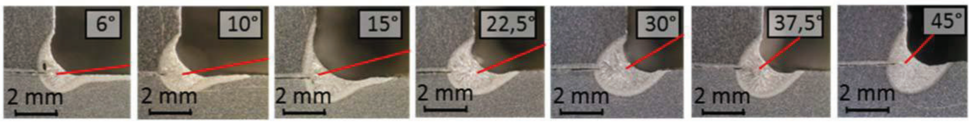

Fig. 6. The shape of the track when laser beam incline angle was varied 6°-45°. Laser power 3 kW, focal distance 40 mm.

From Fig. 6 it can be seen that inclination angle of 45 degrees is most reasonable of all that were tested. Angles from 22.5 to 37.5 has a smaller radius fillet in the undercut. Angles smaller than 22.5 degrees were looked at as potentially beneficial for cases where there is a melt overflow on the root side of the weld. Also they resulted in a very smooth transition to base plate. Especially 15 degree angle case has a beneficial geometry against to fatigue failure. However because of the potentially better all-round melting ability, a 45 degree angle was chosen for the root sealing experiments.

3.4. Sealing run welding tests

Re-melting during sealing run welding increased the quality of the root side regardless of its initial state. Fig. 7 shows the top views of the root sides of the welds prior and after the sealing run welding. Sealing runs made with both of the focal point positions improved the root side profile and smoothed out any discontinuities.

As can be seen from Fig. 7, all of the sealing run welds, done either with 25 mm or 40 mm focal point distances, are similar to each other. The main difference between the two focal point distances used is the width of the weld, Fpp 25 mm produced a narrower bead than Fpp 40 mm. Fig. 8 shows the cross-sections of the welds presented in Fig. 7.

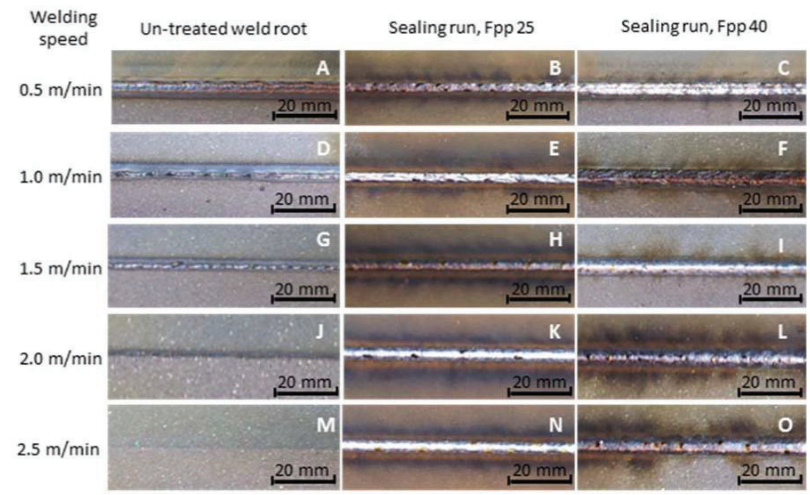

Fig. 7. The weld root appearances before the sealing run welding and after the sealing runs made with 25 mm and 40 mm focal distances.

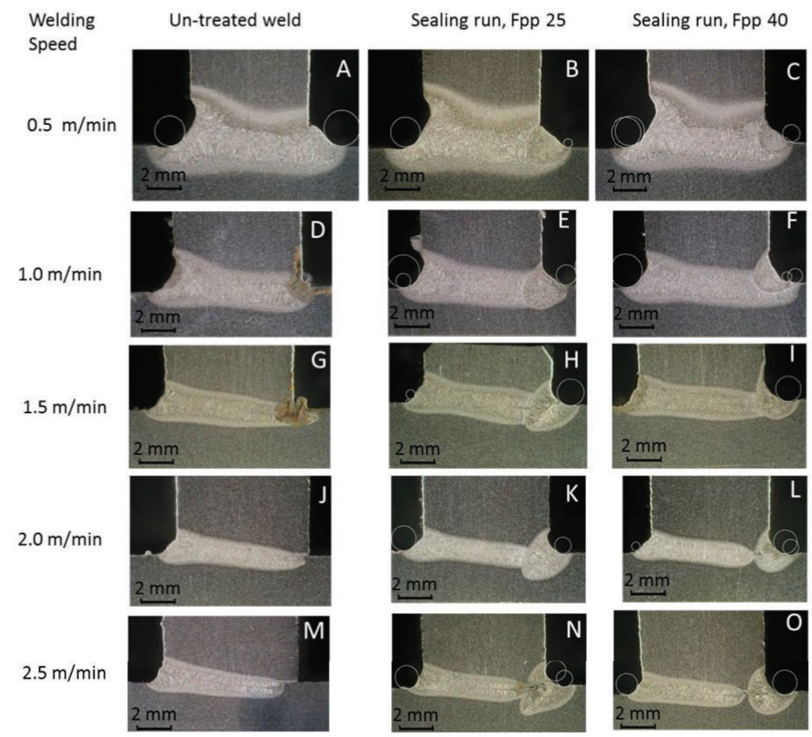

Fig. 8.Macrographs of the cross-sections of the weld samples with and without welding of the sealing run.

To compare the outcomes of the root sealing, the transverse sections showing the penetration and root characteristics of the welds are collated in Fig. 8. None of the welds shown in Fig. 8 have welding defects such as cracks, pores or undercut in the root side. Sealing run welds have shown to compensate for original lack of penetration occurring with fastest welded fillets, however in welds having none of the root side melt formations from the primary run the sealing pass is a bit digging into the material, causing a flaw called root concavity.

The beam angle used in all of the sealing run experiments was 45°, and such flaw is likely avoidable if the beam incline angle is smaller, in between of 20°- 30°. The smaller beam spot, at 25 mm focal point distance, is more suitable to be applied in cases when there is an excessive melt on the root side (Fig. 8 D, G), while larger spot size (Fpp 40, Fig. 8 J, M) is more beneficial when lack of penetration of first weld is evident. With the slowest speed the root side seem to have good geometry even before the seam runs. If this kind of root quality is constant the weld detail does not benefit from the seam weld. In the cases of faster welding speeds, sealing weld clearly improves the quality of root side and extends the fatigue life of the detail.

4. Conclusions

In this paper, the influence of sealing run welding with de-focused laser beam on the weld quality of the 8 mm thick AH36 fillet joint has been investigated.

Welding of a T-joint with fillet weld from one side is a demanding case when full penetration is required. The control of the root side of penetration can be too difficult a case. In this study the quality of the T-joint laser welds is good, corresponding to quality levels B and C.

The quality of the C class welds can be improved by sealing run welding, which eliminates the root side defects such as irregular melt formations and eliminates minor lack of penetration.

The improvements in weld quality will result in improved reliability and longer fatigue life under service.

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Publication III

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Effect of welding parameters and the heat input on weld bead profile of a laser welded T-joint in structural steel

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Effect of welding parameters and the heat input on weld bead profile of laser welded T-joint in structural steel

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The high power fiber laser has become one of the most efficient energy sources for deep penetration welding processes used in heavy manufacturing and marine industries. Combinations of cost-efficient, easily automatable process together with fairly mobile and flexible welding equipment have raised high expectations for improved quality and economic feasibility. In this study, the fillet welding of a low alloyed structural steel was studied using a 10 kW fiber laser. Plates of 8 mm thick AH36 were welded as a T-joint configuration in flat (1F) and horizontal (2F) positions using either an autogenous laser welding or a hybrid laser arc welding process. The effect of heat input on the weld bead geometry was investigated using one variable at a time approach. The impact of single process parameter such as laser power of 4.5–6 kW, welding speed of 0.5–2.5 m/min, beam inclination angle of 6°–15°, focal point position of −2 to +2 mm, and welding positions of 1F and 2F were studied. All welds were visually evaluated for weld imperfections described in EN ISO 13919-1 standard. Penetration depth, geometries of the fusion and heat affected zones, and hardness profiles were measured. Produced joints have a high depth to width ratio and a small heat affected zone; full penetration welds with acceptable weld quality on both sides of the joint were produced. The parameter configurations for optimizing the welding processes are proposed. © *2015 Laser Institute of America.*
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Key words: laser beam welding, low alloyed steel, T-joint, weld penetration

I. INTRODUCTION

Laser and hybrid laser arc welding (HLAW) are high power density processes, making full penetration welds possible in single run at high welding speed and low heat input.[1,2] Up to date, most of the research in laser welding has mainly been concentrated either on butt joint or lap joint configurations. However, the welding of fillet joint is of great importance as well, since most of the welded products having three-dimensional shape require welding of fillet joints.

Welding of fillets in medium thickness steel (4–12 mm) with HLAW has been studied using Nd:YAG laser-MAG hybrid technology; welds with characteristics fulfilling shipyard specifications were produced.[1,3] In the previous studies, it has been noticed, e.g., that welding of a fillet joint is easy due the fact that weld is bending according to the joint, i.e., the effect of the angle of incidence is less severe than in case of butt joint. This is demonstrated in Fig. 1. The phenomena are stronger in case of Nd:YAG laser which has significantly worse beam quality than the CO_2 laser.

Beam quality and output power level of fiber lasers are superior to those of Nd:YAG lasers leading in either deeper penetration or higher speed in practical welding applications. The flexibility of beam delivery by fiber allows accessing difficult joint locations and utilizing novel design solutions in manufacturing of steel structures. This, together with efficiency of laser equipment in case of modern solid state lasers, leads to much higher overall efficiency of the process from wall plug to welding process. The effect of the diameter of the focused beam on welding speed can be noticed very clearly from Fig. 2.

Hybrid welding has additional parameters that influence the process behavior and the properties of the resulting weld. The capability of fiber laser-MIG in welding of fillet welds in 4 mm structural steel has been studied with attention to most influential parameters affecting the weld bead profile.[6] These parameters are laser power, welding speed, focal point position (ffp), air gap, and beam inclination angle.[4,6,7] In addition, focal point position has been shown to have significant effect on the penetration depth and geometry of the weld in butt joint and bead on plate configurations[8] and it should be studied in T-joint arrangement as well. In hybrid welding, typically, the laser process is creating the deep and narrow weld, while arc process aids at the bead geometry formation and brings additional heat to the joint.[1,9,10]

In traditional arc welding processes, the size of the external fillet is considered to be the most important dimension of the joint. The design codes are based on the dimensions and height of the fillet. In arc welding processes, less than half of the plate thickness is penetrated and taken in account in

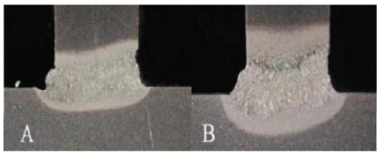


FIG. 1. Welds welded with the highest welding speed to achieve full penetration (a) CO_2 laser weld, $P_L = 5$ kW, $v_w = 0.9$ m/min. (b) Nd:YAG laser weld, $P_L = 3$ kW, $v_w = 0.3$ m/min. S355K2G3 steel with web thickness of 6 mm (Ref. 4).

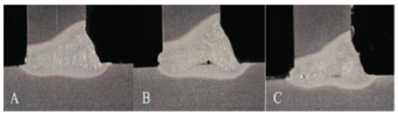


FIG. 3. Illustration of weld flaw caused by misalignment of laser beam in case hybrid welding with CO_2 laser in case of (a) air gap of 0.5 mm, $v_w = 1.3$ m/min, (b) air gap of 0.5 mm, $v_w = 1.1$ m/min, (c) air gap of 0.5 mm, $v_w = 1.5$ m/min. $P_L = 5$ kW, material S355K2G3 steel with web thickness of 6 mm (Ref. 4).

further evaluation of the joint performance. Thus, convex top profile of the bead and high fillet are preferable, because large weld throat means better structural integrity and is advantageous for fatigue life. This regulation cannot directly be transferred to the welds produced with laser based processes, as joints are formed along the interface of the flange and the web throughout the whole thickness. Height of the external fillet is of secondary importance, as weld has usually full penetration with only fraction of the joint situating above the interface of the plates forming a fillet. In laser and HLAW, the concave shape of the top bead is beneficial, as less added filler material means smaller heat distortions and smooth transition from weld bead to base material. In addition, the defects such as undercut are also less likely to appear.

The hybrid welding joint preparation tolerances are less severe compared to requirements of autogenous laser welding. However, the geometrical parameters of the process, such as beam incidence location, are still critical in case of T-fillet joint. Figure 3 shows an example of a case of misaligned beam.

The aim of this study was to investigate the effect of heat input and process parameters on the weld geometry and penetration. Welding position, laser power, welding speed, focal point position, and beam inclination angle, being the most notable variables affecting the shape of the weld bead, were systematically studied. The flat welding position 1F (PA) is the most suitable position for evaluating the capability of the fiber laser based system due to ease of accessibility. The horizontal position 2F (PB) is in practice common for most industrial applications. Figure 4 shows a schematic representation of the welding positions and the cross section of fillet weld produced by either laser welding or HLAW.

Effective throat (t_{eff}) is the shortest distance between the top bead and the end of fusion zone measured along the weld. Penetration depth (d_{pen}) shows the range of the fusion and is measured from the edge of the web to the end of the joint. Width of the weld bead (w_w) is measured across the joint from one toe of the weld to the other and depth of the weld (w_d) is measured from the top surface to the end of the weld.

II. EXPERIMENTAL SETUP

A. Materials

The materials used for this study were 8 mm thick shipbuilding steel AH36 as a base material and G3Si1 as a filler wire. The workpieces were laser cut to dimensions of 350 mm (length) × 100 mm (width) and grid blasted prior to being tack welded in inverted T-position. The chemical composition of the steel and the filler wire are shown in Table I.

B. Laser equipment

A continuous wave fiber laser YLR 10000 emitting wavelength of 1070 nm and having 10 kW maximum power output was used in this study. Focal point diameter of the laser beam was 0.56 mm, resulting from 300 mm focusing mirror, 125 mm collimation mirror, and ø 200 μm process fiber. Kugler LK190 mirror optic laser welding head was used in both test setups. The length of the weld was 165 mm. The main process variables are shown in Table II.

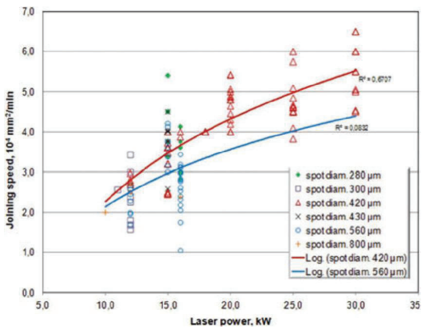


FIG. 2. Joining speeds achieved as a function of laser power for various optical setups and spot diameters used. The lasers used are fiber and disk lasers (Ref. 5).

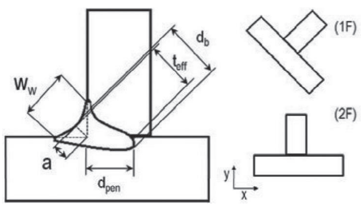


FIG. 4. Schematic illustration of laser/HLAW welded fillet joint (left) and welding positions studied (right).

TABLE I. Chemical composition of the materials.

Material	C	Si	Mn	P	S
AH36	0.18	0.03	0.7	0.035	0.035
G3Si1	0.1	0.9	1.5		

Autogenous laser welding tests were carried out without shielding gas; in HLAW, Ar + 5 CO_2 with flow rate 20 l/min, delivered through the MAG welding torch, was used. In HLAW experiments, the Kugler welding head was combined with a Binzel MAG torch. Kemppi ProMig 530 arc power supply with only pulsed arc setting was used. The synergy setting was constantly on; thus, arc current and voltage were dependent on the welding speed by the feeding speed of the filler wire. The arc was the leading process. Previous experiments have shown that such arrangement generally results in higher quality welds, namely, smoother bead top profile and less root porosity in the joint. The experimental setups are shown in Fig. 5.

C. Test methods

After welding, a quality of weld beads was visually evaluated to detect common weld imperfections described in EN ISO 13919-1 standard. Special attention was paid to imperfections like undercuts, excessive penetration, and lack of penetration due to their effect on the fatigue properties of the weld, where they act as a notch for crack initiation.

Welds having a good bead quality were cut transverse to the welding direction, polished according to standard procedures, and etched with solution of 5% HNO_3 + C_2H_5OH to obtain the geometry of the weld. Subsequently, macrographs were prepared and critical measurements mentioned in Fig. 1 were taken. Macrohardness was measured along the fusion lines using HV 5 with 0.4 mm intercept between the indentations.

1. Heat input

Line energy was used as a common denominator for a comparison process of the welding positions 1F and 2F. Heat input defines the geometry of the joint and can be controlled by a modification of the welding parameters. The heat input

TABLE II. Welding parameters.

Material	AH36
Plate thickness (mm)	8 mm
Welding speed (m/min)	0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5
Laser power (kW)	4.5, 5.56, 6, 8, 8.4, 9, 9.5
Focus position (mm)	+2, 0, −2
Beam angle from flange (°)	6, 10, 15
Arc-laser process distance (mm)	3
MAG torch tilt angle (°)	45
MAG torch travel angle (°)	58
Filler wire feed rate (m/min)	Welding speed × 5.2
Filler wire stick out (mm)	15
Filler wire diameter (mm)	1.0
Air gap in HLAW	0.5

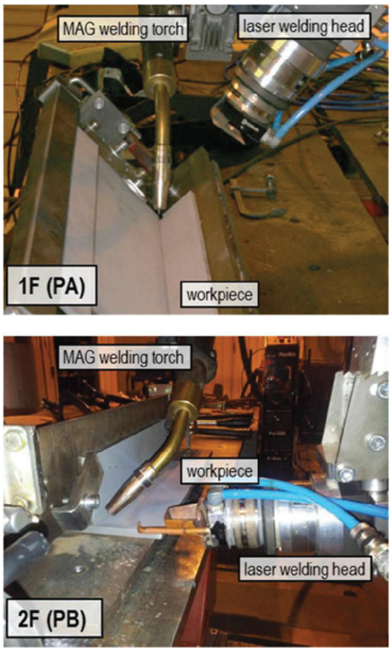


FIG. 5. Experimental setups.

is directly related to the laser (and, if used, arc) power and the welding speed. Heat input for the laser welding was calculated according to the following equation:

$$Q_{laser} = P_L / v_t, \quad (1)$$

where Q_{laser} is the heat input of laser (kJ/mm), P_L is the laser output power (kW), and v_t is the travel speed (mm/s). Heat input of the HLAW is taking into account the additional energy delivered by arc and is calculated by the following equation:

$$Q_T = Q_{arc} + Q_{laser} = (U \cdot I \cdot 60)/v_t + (P_L \cdot 60)/v_t \quad (2)$$

where Q_{laser} is the heat input of laser welding (kJ/mm), P_L is the laser output power (kW), v_t is the travel speed (m/min), Q_T is the heat input of HLAW (kJ/mm), Q_{arc} is the heat input of arc welding (kJ/mm), U is the voltage of arc (V), and I is the current of arc (A).

Laser power used in these experiments was varied between 4.5 and 6 kW and welding speed was varied between 0.5 and 2.5 m/min.

III. RESULTS AND DISCUSSION

A. The effect of the focal point position

Focal point position influences significantly the stability of the welding process, penetration, and quality of the weld. Three focal point positions were tested for studying the

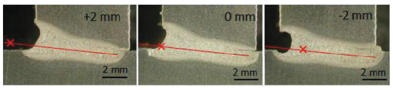


FIG. 6. Cross sections of laser welds produced with focal point positions above, on top, and below the joint. $P_L = 4.56\,kW$, $v_w = 1$ m/min.

effects on penetration depth and geometry of the top of the weld bead. The tests were made in flat (1F) welding position.

Figure 6 shows the results of three focal point positions tested in autogenous laser welding experiments. The heat input was 270 J/mm for all three welds. Beam inclination angle was 6°; the beam propagation and position of the focal point are illustrated on the macrographs.

Figure 6 shows that the penetration is deepest when the focal point is below the surface. The area of the melt and width of HAZ are similar in all three positions, but the location of the weld with respect to web is shifted inward of the joint along with focusing. Comparing the three focal point positions tested, it can be seen that focusing the beam on top of the joint or inside of the material results in sinking of the weld and formation of the undercut. The width of the weld fusion zones is less than 2 mm; in all cases, the weld has crossed the joint plane and missed the root of the joint, restricting the length of the effective throat. Full penetration was not achieved even in case of fpp of −2 mm, when the melt was pushed through the joint, appearing on the root side (see Fig. 6 right). However, used heat input was sufficient for producing weld throughout the thickness at fpp of −2, in case of correct beam positioning (at smaller inclination angle or higher along the web). Narrow weld width and the beam position with respect to the joint (aiming exactly at the point between web and flange) were limiting the fusion at the root.

Figure 7 shows hybrid welds produced with focal point positions above and below the material.

These welds were made under same parameters with exception of the arc power. Although the welding speed and rate of the filler wire feeding were set to same values, 0.8 kW difference in arc power occurred. The corresponding heat inputs were 462 J/mm (fpp of −2 mm) and 414 J/mm (fpp of −2). Regardless of the smaller arc power that weld produced with fpp of −2 mm received, the trend observed earlier in autogenous laser welding was noticed. fpp inside of the material lets energy to be absorbed in the melt pool more efficiently. This can be seen from the geometry and the surface area difference of resulting joints. The weld obtained with fpp of +2 mm had greater arc energy input than fpp of −2 mm; however, the melt areas of the welds, 14.2 mm^2 (fpp of +2 mm) and 17.3 mm^2 (fpp of −2 mm) show that more energy was available to weld to form when focusing was below the workpiece surface.

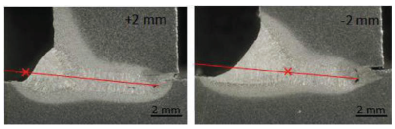


FIG. 7. Cross sections of HLAW welds, fpp of +2 (left) and fpp of −2 mm (right). $v_w = 1$ m/min, $v_{wire} = 5.2$ m/min, $P_L = 4.5\,kW$, $P_{Arc} = 3.15\,kW$ (left) and 2.34 kW (right).

The difference in penetration depth, slightly exceeding 6 mm in both fpp's tested, is minor. However, the influence on the top bead geometry is obvious: fpp above the base material results in narrow weld having convex face bead profile, while fpp inside of the joint creates wider weld with concave face bead profile. As mentioned earlier, the filler wire feeding rate was the same for both welds, and yet the weld produced with smaller heat input has larger melt area, and the amount of the base material melted during the welding process is more than it was when the beam was focused above the joint.

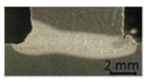
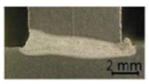
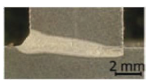
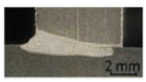
B. The effect of the welding position

Table III presents the welds produced with autogenous laser welding using identical process parameters in positions 1F and 2F.

From figures presented in Table III, it can clearly be seen that the welding position affects the weld geometry and depth of the penetration. The fusion zone of the welds produced in horizontal position is slightly wider and also the penetration is inferior to welds made in flat position.

As expected, the penetration depth and width of the bead lessen with increase of the welding speed in both studied positions. At welding speed of 1.25 m/min, the welds have similar geometry of fusion and heat affected zone, but as welding speed is increased, the differences occur. Weld made in flat position at 1.75 m/min has full penetration with narrow fusion zone and HAZ, while weld made in 2F has partial penetration, 6.2 mm. In the horizontal position, the root of the weld is wider, which, generally, is beneficial from the gap bridging point of view (the beam is more likely to hit the joint plane instead of penetrating the flange). The loss of penetration depth is more noticeable in horizontal position, especially at higher welding speeds. This may be caused by the effect of gravity on the movement of the molten steel,

TABLE III. The effect of the welding position on the weld profile at different welding speeds. Laser welding, $P_L = 6\,kW$, fpp = −2 mm.

Welding speed	Flat (1F)	Horizontal (2F)
1.25 m/min		
1.75 m/min		
2.25 m/min		

because in the horizontal position the melt pool is supported by the flange, while in the flat position the hydrostatic pressure forces the melt to flow rapidly downward. Because of this, an air gap between the plates would increase the penetration depth in flat position.

C. The effect of the inclination angle of the beam

The smallest possible beam inclination angle that was accessible by the equipment used, 6° from the flange, was taken as a starting point. The beam was positioned 0.5 mm above from the joint on the web plate and focused 2 mm below the material top surface in all cases. Sound welds with complete fusion on the root side were produced using 6 kW laser power at welding speeds up to 1.25 m/min, subsequently the beam angle was increased to 10° and 15° to observe whether the penetration is maintainable at higher angles and observe the direction of weld propagation. All welds displayed in Fig. 8 are made in horizontal welding position (2F) with heat input 288 J/mm.

From Fig. 8, it can be seen that the welds are aligned in the direction of the beam. Unlike welds made with CO_2 and Nd:YAG lasers,[4] the welds produced are not bending along the joint plane. The straight and narrow needlelike fusion zone, distinctive to fiber laser welds, was observed.

In the case of 6° angle, full penetration was obtained as adequate amount of melt was pushed through on the root side, forming a sound joint. This phenomenon did not occur in larger beam angles, since the energy was directed linearly and the needle-like weld was formed in the base plate. High density of the beam creates narrow weld, fusion zone does not reach the root region, and under-filling occurs when the beam is missing the joint plane. The area of the fusion zone gradually decreased by change of the beam inclination angles from 10° to 15°, while width of HAZ remained the same. Weld made with the 10° angle had effective throat of 6.8 mm, at 15° angle of 4.3 mm. The penetration depth is also decreasing with increasing beam angles; perhaps the reason is that the beam can be absorbed more efficiently in the melt front when its inclination angle is adjacent to the joint. Small beam inclination angle to the flange is preferable for increasing penetration at any given power and speed combination; however, practical applications may have limitations set by dimensions of equipment and restricted accessibility.

D. Effect of the heat input on weld geometry

1. Laser welding

Figure 9 shows the effect of heat input on the dimensions of the laser welds made in flat (1F) and horizontal (2F) positions.

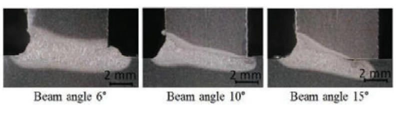


FIG. 8. The effect of the beam incline angle on the weld propagation. $P_L = 6$ kW, fpp = −2 mm, and $v_w = 1.25$ m/min.

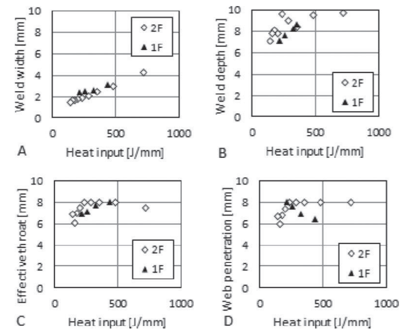


FIG. 9. The weld dimensions under same heat input in 1F and 2F welding positions. fpp = −2 mm and beam angle of 6°.

Figure 9(a) shows that the width of the weld bead (w_w) is increasing as heat input increases. The welds made in 1F at high welding speeds were slightly wider than welds made in 2F with corresponding heat input. This difference was diminished when heat input is greater than 350 J/mm.

The depth of the weld (d_w), measured from top of the bead to end of the fusion zone regardless whether the weld is hitting the seam or not, was similar in range of 300–500 J/mm [Fig. 9(b)]. When heat input was less, the welds made in 2F position were deeper. The difference is explained by different top bead profile, which was rather straight or slightly concave in 2F, but always concave in all of the welds produced in 1F position. This becomes clearer from Fig. 9(c) that the dimensions of effective throat of welds produced in 2F were longer than those made in 1F. The gravity, pulling the melt during welding and solidification, forms concave top bead in 1F position, sometimes causing undercut and sagging of the weld, especially at higher heat inputs when the melt pool is larger. In 2F position, the movement of melt was more restricted as gravity acts from different direction. The melt movement is slower; heat is dissipated into base material, resulting in wider HAZ and higher top bead.

Figure 9(d) shows how much of the web plate was melted, e.g., the reach of penetration along the web–flange interface. Again, it must be noted that not in all of the cases the weld was aligned along the seam, sometimes crossing it and hitting only the flange. Full penetration or 8 mm penetration is reachable with heat input above 260 J/mm in both welding positions. However, the range for acceptable quality is differing, as 1F position results in undercut when heat input exceeds 350 J/mm. Figure 10 displays two welds made in different welding positions with same heat input, 360 J/mm, using 6 kW laser power and 1 m/min welding speed.

The energy distribution is different in the welds shown in Fig. 10. The HAZ of the weld produced in 1F position is narrow and the fusion at the root of the weld is thorough, the melt has flown through the seam and solidified on the back of the joint. Weld produced in 2F position, pictured

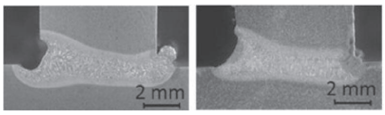


FIG. 10. The weld geometry in 1F (left) and 2F (right) welding positions at heat input 360 J/mm. fpp = −2 mm and beam angle of 6°.

on the right, has received same amount of energy, yet the geometry of the fusion zone and dimensions of surrounding HAZ are larger. HAZ is wider throughout the joint, and the fusion at the root is not as complete as it was in 1F position.

The shape of the top bead of the 1F weld can be characterized as concave; the top of the weld bead has sunk. For improving the quality of the fillet under existing setup, heat input has to be decreased, either by increasing the welding speed or by decreasing the laser power. The bead of the 2F weld is also concave; bead has smooth junction to base metal and corresponds to demands in standards. However, judging from the geometry of the root, this weld requires more heat input to be completely sound throughout the whole length of the seam. This phenomenon becomes less noticeable as the heat input decreases (see Table III welds made with welding speed of 1.75 and 2.25 m/min). Apparently, the parameter window for heat input seems to be narrower in case of 1F than in case of 2F, horizontal position also requires higher heat input for producing full penetration.

2. HLAW

Figure 11 shows the effect of heat input on the geometry of the hybrid welds, only 1F welding position was used.

The areas of melt and HAZ increased linearly with increasing heat input [Figs. 11(c) and 11(d)], same can be said of the width of the weld bead. However, there is no straightforward correlation to dimensions of effective throat [Fig. 11(b)]. The depth of the penetration is primarily dependent on the laser power and full penetration welds with narrow melt area were produced at low heat inputs as well, as long as there was sufficient laser power available. Figure 12 shows how the geometry of the bead is changing depending on the heat input.

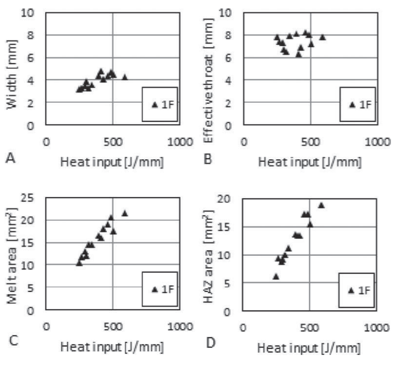


FIG. 11. The effect of the heat input on the weld dimensions in hybrid welding. fpp = −2 mm and beam angle of 6°.

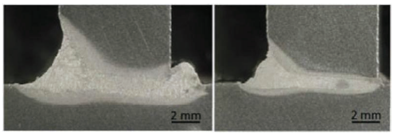


FIG. 12. The change in weld geometry in respect to heat input. $P_L = 6$ kW, fpp = −2 mm, $v_w = 1$ m/min (left) and 2.5 m/min (right).

Figure 12 displays the welds preformed with the same laser power at heat inputs of 494 J/mm and 255 J/mm. The area of the fusion zone is correlated to heat input, as welding speed is increased, the weld narrows, but maintains the needlelike profile. While maintaining complete penetration, the weld shown on the right in Fig. 12 has a solidification cracking defect close to the root, which is common for high welding speeds.

E. The effect of the welding speed on hardness

Hardness is one of the most important critical factors indicating the quality of the weld and its performance in service. The hardness of the shipbuilding steel AH36 was measured to be HV 170. Maximum allowable peak hardness according to the classification societies related to ship production applications is 380 HV and hardness should be kept under 350 HV. In this study, the hardness was measured along the fusion lines of the laser and HLAW welds produced at corresponding welding speeds. All of the welds displayed in Fig. 13 were made with 6 kW laser power and fpp of −2 mm.

At 2.25 m/min welding speed, the HLAW weld has full penetration, while laser weld has lack of fusion in the root side. When comparing the welds produced with 1 m/min welding speed, interesting phenomena occurred—hardness is lower in laser weld than in hybrid weld throughout the joint. Corresponding heat inputs are 300 J/mm for laser weld and 430 J/mm for hybrid weld. As welding speed is increased (heat input becomes smaller), situation is changed, thus, higher welding speed (insufficient heat input) is the cause of increased hardness and smaller penetration. Addition of the filler wire and larger heat input in HLAW slows cooling of the weld, resulting in smaller peak hardness.

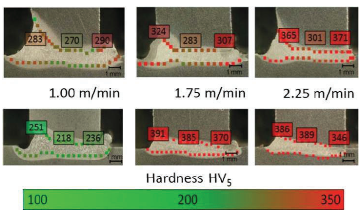


FIG. 13. The macro-indentation hardness profiles of the T-joints made with corresponding speeds using HLAW (up) and laser welding (down).

IV. CONCLUSIONS

In this study, the effects of focal point position, beam inclination angle, welding position, and heat input on the geometry of the fillet welds produced with laser and HLAW were examined.

In both welding processes, the focal point position below the workpiece surface results in deeper penetration. However, in the case of laser welding process, this results in under-filled top bead, while in HLAW process, the preferred concave top bead is achieved due to the filler wire added.

The welds produced in 1F position were deeper than those welded in 2F position, having narrower fusion and HAZ. The gravity likely increases the melt flow inside of the melt pool in direction of the seam resulting in deeper penetration in 1F welding position.

Beam inclination angle is a major factor influencing the penetration, as the weld is narrow and propagating along the beam path. For obtaining full penetration, the beam should be positioned in a way that it passes the root of the weld or the melt pool reaches the root side. This can be achieved by increasing the distance of the beam from the flange while simultaneously increasing the inclination angle.

Increasing the heat input increases the size of the melt area, HAZ, and width of the weld, while there was no straightforward correlation to penetration depth, which is strongly dependent on laser power.

The hardness, measured from the fusion lines of the weld, was rather uniform throughout the sample thickness. The hardness of the welds produced at higher welding speeds was below 400 HV, remaining in acceptable range for AH36 material at welding speeds up to 2 m/min.

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Publication IV

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Influence of filler wire feed rate in laser-arc hybrid welding of T-butt joint in shipbuilding steel with different optical setups

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Influence of Filler Wire Feed Rate in Laser-Arc Hybrid Welding of T-butt Joint in Shipbuilding Steel with different optical setups

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Abstract

In this paper, a study of laser-arc hybrid welding featuring three different process fibres was conducted to build knowledge about process behaviour and discuss potential benefits for improving the weld properties. The welding parameters affect the weld geometry considerably, as an example the increase in welding speed usually decreases the penetration and a larger beam diameter usually widens the weld. The laser hybrid welding system equipped with process fibres with 200, 300 and 600 μm core diameter were used to produce fillet welds. Shipbuilding steel AH36 plates with 8 mm thickness were welded with Hybrid-Laser-Arc-Welding (HLAW) in inversed T configuration, the effects of the filler wire feed rate and the beam positioning distance from the joint plane were investigated. Based on the metallographic cross-sections, the effect of process parameters on the joint geometry was studied. Joints with optimized properties (full penetration, soundness, smooth transition from bead to base material) were produced with 200 μm and 600 μm process fibres, while fiber with 300 μm core diameter produced welds with unacceptable levels of porosity.

Peer-review under responsibility of the Lappeenranta University of Technology (LUT)

Keywords: fiber laser; laser-arc hybrid welding; weld geoetry; T-joint; shipbuilding steel

1. Introduction

Wide range of welding processes involving laser as one of the energy sources are under active development (Stiles, 2010). Majority of the welding work in industries dealing with sheet metal joining is still carried out using GMAW

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(Gas Metal Arc Welding), however switching to laser-arc hybrid welding (HLAW) would bring significant economic benefits. HLAW could be suitable for large number of serial production applications where throughput volumes are high. In HLAW, the beam and the arc act simultaneously, support each other and in comparison to laser welding produce improved gap bridgeability and in comparison to arc welding higher processing speeds, increased quality, less distortion and thus less re-work and shorter production times (Kristensen et al., 2009). It provides combination of "properties" that usually would be mutually exclusive. Typically, due to laser beam penetration ability and synergy of the processes, only one pass is required to form a solid joint. Additionally, the workpieces are subjected to smaller heat input, which reduces distortions and the need for post welding corrections, thus saving time and money (Reutzel et al., 2008). The reasons of HLAW not being more widespread is that it is seen as a complex process with high number of variables involved and expensive initial investment. However, many process parameters can be changed and still a sound weld can be deposited, because the quality window of HLAW is significantly larger than that of autogenous laser welding (Gumenyuk et al., 2013).

The areas of applications of structural steel range from assemblies on land, heavy industry vehicles to offshore platforms and power plants. The final product is often subjected to both, static and dynamic loading and good weldability is essential for safety and long life cycle of the components. Laser and HLAW processes deliver reduced amount of heat to the joint and use less, if any, consumables to form a solid connection, therefore having both, metallurgical and economic benefits, most notable being the greatly reduced costs on the post-weld straightening and correction work (Cao et al., 2011). Both of the processes are very versatile and automatable, which contributes to uniformity of the welds produced and high repeatability of the process.

Autogenous laser welding has had vigilant reception by industry regardless of aforementioned benefits. The small amount of adjustable process variables simplify finding the optimal process parameter window. Due to small dimensions of the tightly focused laser beam spot on the surface, the factory floor solutions are at times unable to comply with extremely precise part positioning requirements, especially when the welds are long and joint gap is changing because of metal heat expansion or slight distortions which might occur during the welding (Salminen et al., 2010). On the other hand, in automotive and other industries where material thickness is small and lap, butt and eccentric fillet joints are common, benefits of autogenous process are the greatest. Regardless of relatively simple setup and vast savings in material (joint is formed from the workpiece material without additional fillers), low gap bridging capacity and small parameter window for acceptable quality welds are seriously hindering wider use of autogenous laser welding in production of structures with T-butt and fillet joints, the risk of the beam misalignment from the joint being the key problem (Dilthey et al., 1995).

In HLAW process the energy to form a weld is delivered by two sources acting in synergy. Laser beam is responsible for penetration depth and high welding speed, while arc process allows bridging wider gaps, defines the shape of the bead (Rayes et al., 2004). GMAW delivers additional heat that slows down the cooling and helps to avoid the formation of brittle microstructures. The molten pool near the surface is dominated by the arc process, while in autogenous laser welding the molten pool geometry is determining the solidification process, which, in turn, is determined by the keyhole mode (Boley et al., 2013). Laser beam stabilizes the arc, and the processing speed is significantly higher than in arc or laser welding alone. Additionally, the spray transfer of filler material into melt pool is beneficial for mechanical properties of the joint (Ribic et al., 2009). The hardness values in HLAW are lower than those seen in autogenous laser welds, typically not exceeding the 350 HV hardness limit set by the standard for structural steels. Flexible beam delivery and short wavelength of fiber laser have eliminated for example the difficulty of choosing the shielding gas, which is an issue with CO_2 laser-arc hybrid welding. The wavelength of the fiber laser is not prone to creating plasma and therefore the shielding gas choice is based purely on the arc process specification. Study on bead formation in autogenous laser welding of butt and corner joints proposed a matrix flow chart to display the geometries and occurring details systematically (Karlsson et al., 2010). Eriksson et al. (2001) have proposed guidelines of HLAW with fiber laser, focusing on the GMAW side of the process.

To date, several studies have discussed the effects of the beam brightness, spot size and energy density on the welding performance in autogenous process (Kawahito et al., 2008; Verhaeghe et al., 2005 and Suder et al., 2014). In this paper, the influence of filler wire feed rate to HLAW process was identified in order to show its effect on the geometrical dimensions of the weld when combined with high power fiber laser welding using three different optical setups.

2. Materials and methods

Shipbuilding steel AB AH36 plates were laser cut with a CO_2 laser using oxygen as cutting gas to 100 mm × 350 mm plates, grid blasted with aluminium oxide and cleaned with acetone to remove impurities and grease. The filler wire used was 1 mm thick OK Aristorod 12.50, alloyed with manganese and silicon and commonly used for welding of structural and shipbuilding steels like AB AH36. The chemical composition of base materials and the filler wire are shown in Table 1.

Table 1. Chemical composition (wt. %) of the AH36 and filler wire OK Aristorod 12.50

Material	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	V
AH36	0.111	0.149	0.711	0.035	0.150	0.051	0.01	0.041	0.031	0.030	0.008
OK AristoRod 12.50	0.06 – 0.14	0.7 – 1.0	1.3 – 1.6	0.025	0.025	0.15	0.15	0.15	0.35	0.02	0.03

The plates were tag welded together prior to welding the 340 mm long weld using laser-arc hybrid process. All of the experiments were performed with 10 kW IPG Photonics continuous wave fiber laser emitting 1070 nm wavelength. The beam was delivered to workpiece by process fibres with core diameters either 200 µm, 300 µm or 600 µm. The mirror optics laser welding head Kugler LK190 was used with a 300 mm focal lens and 125 mm collimation lens. Parameters of the laser beam of each process fibre can be seen in Table 2. The experimental setup is shown in Fig. 1.

Table 2. The IPG YLS-10000 specification for each process fibre

Fibre diameter (µm)	Output power (kW)	Wavelength (nm)	Rayleigh length (mm)	Divergence angle (mrad)	BPP (mm*mrad)
200	10	1070	10.260	58.228	8.697
300	10	1070	11.600	59.753	10.354
600	10	1070	17.715	74.415	24.525

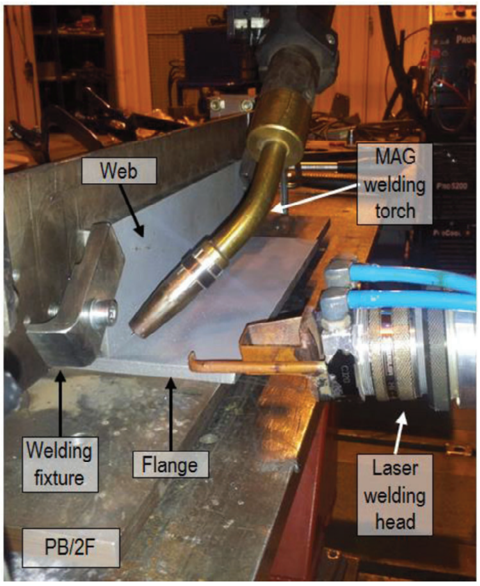


Fig. 1. Experimental setup used for laser and laser-arc hybrid welding of T-butt joint, flat welding position.

ESAB Aristo LUD 450 with Binzel MAG torch was used as an arc power source, the synergy setting, varying the current and voltage based on filler wire feeding rate, was on. For shielding of the surface of the weld from the atmosphere a process gas consisting of Ar + 18 CO_2 was delivered through MAG torch at flow rate 20 l/min. Tilt angle of the arc welding torch was 45 degrees, torch travel angle 58 degrees, free wire length 15 mm and the beam angle from the flange was 15 degrees. The influence of beam lateral displacement along the web from the flange and effect of the filler wire feeding rate were studied. In all experiments, arc was leading the laser beam with process distance 3 mm. Welding speed 1.25 m/min, filler wire stick-out length 15 mm and focal point position -4 mm i.e. 4 mm below the top surface were kept constant. Parameters used in each set of experiments are presented in Table 3.

Table 3. Variables

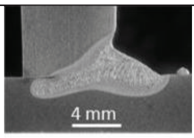
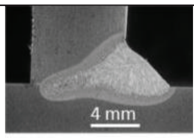
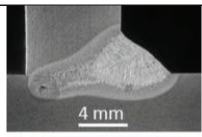
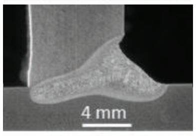
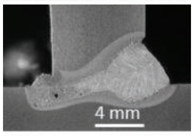
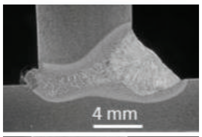
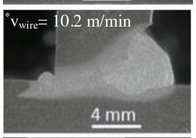
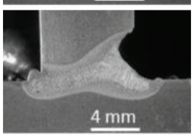
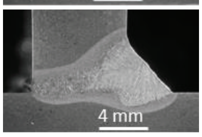
Variable	200 μm process fibre	300 μm process fibre	600 μm process fibre
Laser power on workpiece (kW)	8	8	10
Beam distance from flange (mm)	1.2, 1.5, 2.0	1.2; 1.5; 2.0	1.2; 1.5; 2.0
Wire feed rate (m/min)	5.1 - 12.7	5.1 - 16.6	5.1 - 16.6

3. Results and discussion

3.1. Effect of the lateral position of the beam

The aim of the experiments was to evaluate the capacities of each optical setup and investigate the tolerance limits of beam positioning relative to the joint interface. The dynamics of molten pool or keyhole behaviour were not in scope of current study. The welding speed 1.25 m/min and focal point position -4 mm were kept constant in all setups studied. The arc power setting was based on the given filler wire feed rate due to synergy setting used, thus, more arc energy was involved, thus at higher filler wire feed rates, the arc power, and subsequently its influence of the weld bead geometry, is increased. The preliminary experiments made to evaluate the laser power needed to reach full penetration using autogenous laser welding only showed that appropriate power levels are 8 kW for 200 μm and 300 μm process fibres and 10 kW for 600 μm process fibre. The results are presented in Table 4.

Table 4. Macrographs of T-joints with different filler wire addition rates

Beam distance from flange (mm)	Process fibre Ø = 200 μm P_L = 8 kW v_{wire} = 5.1 m/min		Process fibre Ø = 300 μm P_L = 8 kW v_{wire} = 10.2 m/min	Process fibre Ø = 600 μm P_L = 10 kW v_{wire} = 10.2 m/min
1.2				
1.5		B		
2.0				

First of all, the lower part of the weld shows that the width of the molten pool is correlated to the diameter of the incoming beam. However, the difference is relatively small when comparing the welds produced with 200 μm and 300 μm fibres, but becomes obvious when 600 μm process fibre was used. In all of the setups tested it is seen that the axis of the weld is aligned along the direction of the beam propagation, meaning that if the beam is completely missing the back of the joint, as when positioning distance 1.2 mm was used, the molten pool is not penetrating through the whole plane. However, when keyhole is only slightly missing the end of the joint and the molten pool is wide enough to melt the edges, full penetration is possible, as tests made using offset 1.5 mm show. The melt pool of 200 μm setup is that narrow that the beam did not reach the back side of the joint plane. The weld made with 300 μm setup, being only marginally larger, reaches the root, and part of the melt was pushed through on the back of the weld, but spatter was generated during the welding and overall process stability was not uniform. On the other hand, the weld produced with 600 μm process fibre had uniform root side exceptional quality throughout the length of the weld, showing complete penetration and class B quality according to EN-ISO 139 19-1.

Regarding the beam positioning distance 2 mm, full penetration was produced with all setups. It must be noted, that for the one experiment with 200 μm process fibre and 2.0 mm positioning the filler wire feeding rate was doubled, from 5.1 m/min to 10.2 m/min for the reason that the initial filler wire feeding rate 5.1 m/min was lacking the material to form acceptable weld bead. As soon as the beam axle crosses the joint plane at the root at sufficient laser power melting the edges of the plates, some of the melt is pushed through to the back of the weld. The largest distance from the joint, 2 mm, tested in scope of this study, produced full penetration in all setups used, however, the sufficient quality joint, having smooth bead surface and uniform root bead, was produced only with 600 μm process fibre. The two other setups (regardless of the filler material supplied), both of the welds had top surface bead defects and inconsistent root side quality.

From the industrial point of view, the most versatile solution out of the three process fibres tested would be the 600 μm fibre, as it produces wide melt pool at the root of the weld. Top beads of the welds were superior in quality compared to two other setups studied. The welds made with 200 μm and 300 μm process fibres were deep, yet extremely narrow at the deepest section of the weld which is created by the beam. In respect to the quality of the bead surface, these two setups produced welds, which, due to high beam intensity, had undercuts, regardless of the additional material supplied by the arc. As opposed to laser beam welding without filler wire, HLAW is more stable process that has greater gap bridging ability and also smaller probability for seam imperfections coming from joint fit-up. The high beam density, which might be useful in increasing of the penetration in butt welds, is likely to cause inconsistency in welding of T-joints in many industrial applications due to more sensitive tolerance limits set by standards of pre-fabrication.

3.2. Effect of the filler wire feeding rate

Based on the results of the lateral beam positioning experiments, two values were chosen for further experimentation with filler wire feed rate. The 1.2 mm was picked for setups with 200 μm and 300 mμ process fibres and 1.5 mm for 600 μm process fibre. The setup with 600 μm process fibre was made with 2 kW higher laser power than used in other two setups. However, the results are comparable, because laser power levels were chosen based on producing full penetration in autogenous laser welding. The filler wire feed rates tested were 5.1-16.3 m/min, except in the case of 200 μm setup, where highest value was 12.7 m/min. During the experiments it became clear that full penetration is not possible, and growing weld throat would lead only to decrease in quality. Macrographs of cross-sections are shown in Table 5.

Table 5. Macrographs of T-joints produced while varying the filler wire feed rate

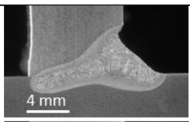
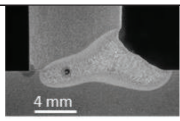
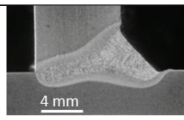
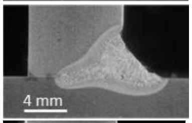
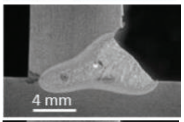
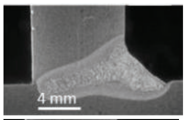
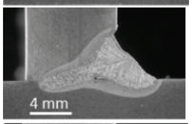
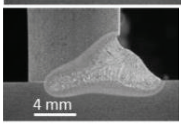
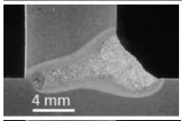
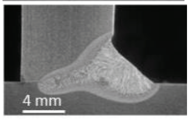
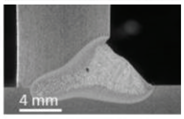
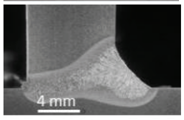
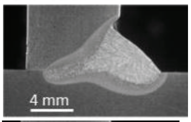
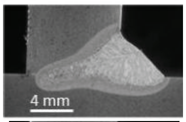
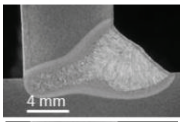
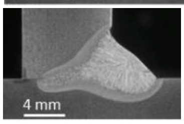
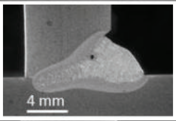
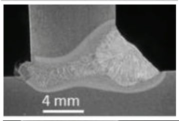
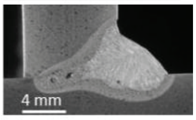
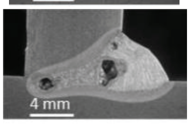
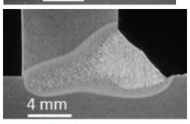
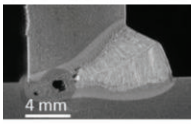
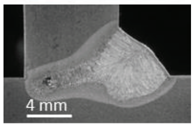
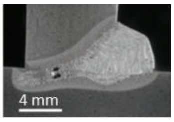
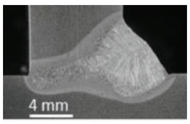
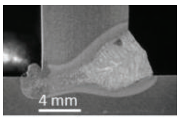
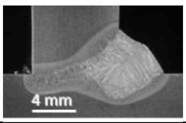
Wire feed rate (m/min)	200 µm process fibre Beam positioning 1.2 mm P_L = 8 kW	300 µm process fibre Beam positioning 1.2 mm P_L = 8 kW	600 µm process fibre Beam positioning 1.5 mm P_L = 10 kW
5.1			
6.5			
7.6			
8.9			
10.2			
11.5			
12.7			
14.0	-		
15.3	-		
16.6	-		

Table 5 outlines the differences between setups. In autogenous laser welding, the ability to penetrate the material is correlated with brightness of the beam, however in HLAW such relationship is not as straightforward. The GMAW process of the hybrid welding is responsible for more than third of the penetration, and, fully affecting the formation of the weld bead. Part of the beam energy that could contribute to penetration is used for melting the extra material as filler wire feed rate increases. Fig. 2 gives an overview of three most critical dimensions of the welds displayed in Table 5.

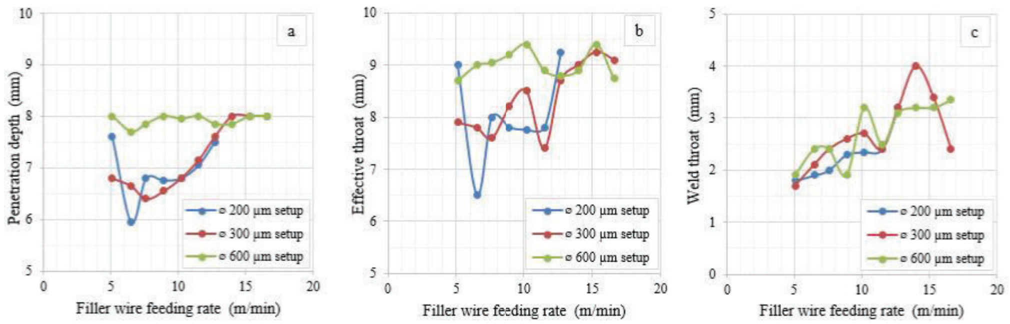


Fig. 2. (a) penetration depth; (b) length of effective throat; (c) height of the weld throat.

Fig. 2 shows the dimensional differences of joints produced with each setup. The welds produced with 200 and 300 μm setups have similar dimensional characteristics (see Fig. 2. a) and are prone to undercuts, especially when filler wire feed rate is less than 12.7 m/min. The setup with 600 μm process fibre did not produce undercuts throughout whole tested range. The depth of penetration was almost constant throughout the tested range, as opposed to two other setups.

The length of effective throat, e.g. the shortest distance between the root of the weld and the top of the bead, is shown in Fig 2. b. All setups are capable to produce effective throats that exceed at least 80% of the material thickness (8 mm). The height of the weld throat (see Fig. 2. c) is growing in accordance of filler wire addition and continues to increase after full penetration is reached and part of the melt is pushed to the root side of the weld. Increasing filler wire feed rate does not contribute to quality improvement, and should only be applied in cases where additional heat is needed to control the hardness.

4. Conclusions

Following conclusions can be drawn:

1) Current trend, the brighter the beam the better, does not deliver good quality in some of the welding cases, such as the high power laser and HLAW of T-joints. According to data gathered in this study, and quality of the top bead and the root being equally important, the 600 μm fibre setup produced slightly wider root and smooth junctions of the top bead with the base material.
2) There should be a certain balance of laser power, welding speed and filler wire feed rate (which was constant during these experiments). In this study, 10 kW laser power was used only with 600 µm fibre to produce the full penetration. Using same power without increasing the speed with other setups is likely to result in melt run out and hardness above 400 HV, thus unacceptable quality.
3) The best results regarding the quality of the joint were produced with 600 μm process fibre set up. The welds had wide root, which is crucial to achieving fusion at the back of the weld. Therefore, for avoid the problems

with the beam positioning, using high laser powers delivered through the 600 μm process fibre widens the process window for acceptable quality.

4) HLAW is a complex process and further studies are needed, for example through monitoring of the welding process with high speed camera in situ, and, also, simulations to get better understanding of melt flow and process physics involved in keyhole behaviour.

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Publication V

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High Power Fiber Laser Welding of Single Sided T-joint on Shipbuilding Steel with Different Processing Setups

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High Power Fiber Laser Welding of Single Sided T-Joint on Shipbuilding Steel with Different Processing Setups

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Abstract: Laser welding of thick plates in production environments is one of the main applications of high power lasers; however, the process has certain limitations. The small spot size of the focused beam produces welds with high depth-to-width aspect ratio but at times fails to provide sufficient reinforcement in certain applications because of poor gap bridging ability. The results of welding shipbuilding steel AH36 with thickness of 8 mm as a single-sided T-joint using a 10 kW fiber laser are presented and discussed in this research paper. Three optical setups with process fibers of 200 µm, 300 µm and 600 µm core diameters were used to study the possibilities and limitations set by the beam delivery system. The main parameters studied were beam inclination angle, beam offset from the joint plane and focal point position. Full penetration joints were produced and the geometry of the welds was examined. It was found that process fibers with smaller core diameter produce deeper penetration but suffer from sensitivity to beam positioning deviation. Larger fibers are less sensitive and produce wider welds but have, in turn, lower penetration at equivalent power levels.

Keywords: shipbuilding steel; fiber laser; laser keyhole welding; T-joint; fillet joint

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1. Introduction

Laser welding with multi-kilowatt fiber lasers is fast becoming a highly advantageous joining technology in manufacturing industries such as shipbuilding, where it saves production time and cost compared to conventional arc based welding processes [1]. The growing acceptance and adoption of laser technology can be seen, for example, in sales statistics, which show an annual growth rate of over 10% for the last few years [2,3]. Modern high power fiber lasers are low maintenance, easy to integrate with production robots, and produce welds with deep penetration and low heat input at high throughput rates [4,5]. High beam quality at high power levels and the decreasing price per kilowatt of laser power are enabling previous limitations to be overcome and opening up new possibilities, especially in keyhole welding. The main limiting factor hindering more extensive utilization of laser welding is its demand for high accuracy in joint fit-up tolerances. A common way to compensate gap fluctuations and ensure welds of acceptable quality is to add an arc process working in synergy with the laser. While such hybrid laser-arc welding allows control of weld bead formation through adjustment of the arc parameters and extends the gap bridging ability of the welding system, it increases process complexity and production costs.

One of the most important characteristics of a laser welding system is the beam quality that the lasers deliver. The beam quality affects the power density of the beam, which has a direct effect on the penetration depth and geometry of the weld [6,7]. High power density of the beam means deeper penetration for the same level of power and welding speed. Single-sided welding of T-joints with fiber lasers is not an entirely novel concept, and its applicability and key parameters have been studied, for example, for aluminum welding in the aircraft industry [4]. The high depth-to-width aspect ratio of typical fiber laser welds can be a drawback in medium and thick section welding of T- and fillet joints. Space and maneuverability restrictions on the welding head can cause the laser beam to cross the joint plane at a certain angle, and a narrow melt pool may easily partially miss the joint plane and produce incomplete fusion. In addition, T-joint welds can be several meters long and heat-induced distortions during welding can thus cause variations in joint fit-up regardless of the accuracy of the original setup.

Classification societies such as DNV (Det Norske Veritas) and IIW (International Institute of Welding) suggest avoiding fillet welds in parts of a construction that are subjected to fatigue, because partial penetration creates a possible crack initiation point at the root of the weld [8,9]. Nevertheless, more than 80% of welded joints are fillet welds, because one of the plates serves as backing during the welding process and less post-welding correction is required. Figure 1 illustrates the principal differences in the geometry and location of the stress concentration of arc, laser and hybrid welded joints.

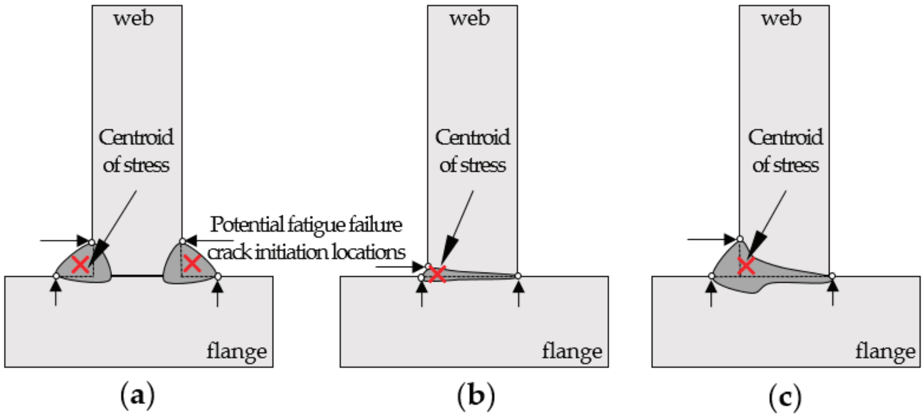


Figure 1. Comparison of weld joint geometries produced with: (**a**) arc welding; (**b**) autogenous laser welding; and (**c**) laser-arc hybrid welding, and stress concentration locations.

The key problem with T-joints is ensuring fusion throughout the whole joint plane, preferably with single-sided welding. In autogenous laser welding, avoidance of the possible occurrence of underfill or undercut due to an absence of filler material is important, because throat thickness and shape of the weld toe influence the fatigue performance of the joint. In thin materials and flat assembly joints, this problem can be addressed by increasing weld width through wider distribution of the beam energy. Approaches used include but are not limited to: manipulation of the focal point position [10], and usage of dual focal point setups [11–13] and beam oscillation techniques [14–17]. Scanning is also beneficial for bringing more heat into the material, which decreases the cooling rate and keeps the hardness of the weld at acceptable levels. Unfortunately, this procedure is not applicable in thick section welding, where the typical weld length is several meters, because scanning mirrors are unable to handle the power levels needed [14,18]. Large components such as scanning optics also limit the degree of freedom and flexibility of the welding process as regards positioning.

Determining the operational window for a good quality weld accounts for three main process parameters: laser power, welding speed and focal point position. These three easily adjustable parameters affect the power density at the top of workpiece, and therefore melt flow and distribution of the energy inside the keyhole, which have a major influence on the geometry of the weld. A certain threshold value of power density must be reached in order to be able to form the keyhole [19].

The threshold is typically defined as 10^6 W/cm^2, or more commonly 10^3 W/mm^2, with typical dimensions of laser beam focal point. The power density is calculated as follows:

$$E = \frac{P}{\pi r^2}, \tag{1}$$

where P is laser power and r radius of the beam on the surface of the workpiece. The above-mentioned power density threshold is valid for CO_2 laser welding, whereas when using solid state lasers with wavelengths around 1000 nm the threshold is lower [20,21]. The lower threshold is a result of higher absorption of shorter wavelengths, and it gives extra flexibility to parameter selection and greater freedom to tailor parameters to specific applications, for example, with static or dynamic beam formation.

Suder and Williams et al. [22] developed the concept of Specific Point Energy (E_{SP}). In addition to energy density (power density × interaction time), E_{SP} includes also beam diameter on the surface:

$$E_{SP} = \rho_P T_i A = P_L T_i = \frac{Pd}{v}, \tag{2}$$

where ρ_P is average power density of the beam (mW/cm^2), T_i is interaction time (s), A is area of the beam on the surface (mm^2), P_L is laser power (W), d is beam diameter on the surface (mm), and v is welding speed (mm/s). Experiments performed with bead-on-plate joints have shown that power density and E_{SP} control the depth of penetration and interaction time controls the bead width [22–24]. E_{SP} has also been shown to be suitable for evaluating the efficiency of laser cutting [25,26].

The relationship between spot size and welding performance in steel and aluminum welding has been addressed in several studies [27–30], and it has been found that small spot size produces deeper welds yet is accompanied by defects such as undercut and porosity. A study by Vänskä [14] showed that in some cases the keyhole welding mode changes between selected parameter values, resulting in different weld cross section shape in butt joint welding of stainless steel with a disk laser. Lap and butt joints produced with CO_2 and solid-state laser sources have been characterized and compared [20]; for example, Kawahito et al. [28] addressed the effect of focal spot size on weld defects and showed that, of the four sizes studied, welds with highest quality were obtained using the two larger spot sizes.

The effect of focal point diameter on beam intensity on surface is much stronger than the effect via laser power. A simple way to manipulate the focal point diameter is to change the focal length of the focusing lens. A problem with this approach is that the focusing angle, i.e., the angle at which the beam enters the keyhole, changes as the focal length is changed, and the effect of focal point diameter is influenced by the effect of focusing angle and changes in the shielding gas arrangement. Change in the beam feeding fiber can only increase the diameter of the raw beam and the beam parameter product. This paper addresses the issue of weld quality of high power fiber laser welded T-joints of shipbuilding steel AH36 by comparing welds produced with three optical set-ups having beam transfer fibers of different diameters.

2. Materials and Methods

Shipbuilding steel AH36 is commonly used for shipbuilding and offshore structures. Hot rolled steel plates of AH36 have excellent weldability with a CEV (carbon equivalent value) of 0.248, calculated based on the chemical composition presented in Table 1. The yield strength of AH36 is 355 MPa.

Table 1. Chemical composition of AH36 steel (wt %).

Material	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	V
AH36	0.111	0.149	0.711	0.035	0.150	0.051	0.01	0.041	0.031	0.030	0.008

Test specimens (100 mm × 350 mm × 8 mm) were cut with a CO_2 laser using oxygen-assisted cutting. The edges were grid blasted with aluminum oxide and cleaned with acetone to remove possible contaminants. The plates were tack welded from the root side from the ends and the middle using gas metal arc welding. The workpiece was fixed in the flat (1F) position using stiff fixtures to avoid heat-induced air gap fluctuations during the welding. Single-sided welds with a length of 165 mm were performed. The experimental setup is shown in Figure 2.

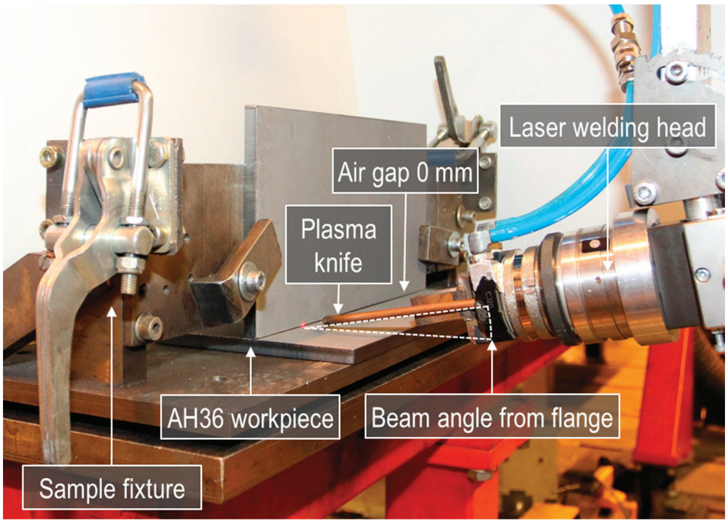


Figure 2. Experimental setup for laser welding of T-joints. Beam is positioned at the joint plane (offset 0 mm).

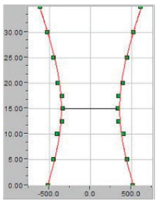
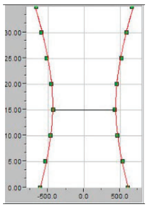
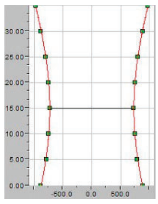
All welding experiments were made with a continuous wave fiber laser IPG YLS-10000 having wavelength of 1070 nm and a top-hat focused beam profile. A Kugler LK190 mirror optics laser welding head was used. An air knife protected the focusing system from contamination with fumes and spatter, and no additional shielding gas was used. When comparing a T-joint with a butt joint, a further parameter, called offset, describing the distance of the beam center from the joint at the flange front edge, must be added. This parameter has a crucial effect on weld quality and must be considered for thick section joints of the type studied in this work. The experimental parameters of the welding process are presented in Table 2.

Table 2. Welding process parameters.

Parameter	Unit	Parameter Range
Fiber diameter	[µm]	200; 300; 600
Laser power, P_L	[kW]	6.0; 8.0; 10.0
Welding speed, v_w	[m/min]	0.75; 1.0; 1.25; 1.5; 1.75
Focal point position, F_{PP}	[mm]	−2.0; −4.0; −6.0
Beam angle from flange α	[°]	6; 10; 15
Beam offset from flange	[mm]	0.5; 1.0; 1.2; 1.5; 2.0

The beam was delivered by a system consisting of a beam transfer fiber (with core diameters of either 200, 300 or 600 µm), 120 mm collimating length optics, and a 300 mm focal length mirror. The properties of the laser beam emitted from each transport fiber were measured using a laser beam analyzer from Primes GmbH and are shown in Table 3.

Table 3. Beam properties.

Delivery Fiber Diameter (µm)	200	300	600
Beam profile			
Nominal beam waist (mm)	0.50	0.75	1.50
Measured beam waist (86% pts) (mm)	0.710	0.882	1.460
BPP (mm·mrad)	9.079	12.000	23.800
Rayleigh length (mm)	13.86	16.18	22.38
P_L at workpiece (kW)	6.0	6.0	6.0
Beam area at surface (mm^2)	0.396	0.611	1.674

The bead surface and root of each weld were visually evaluated based on standard EN ISO 13919-1, which classifies welds into three quality levels based on the type and severity of the imperfections that are present. The categories from best to worst are: B, stringent; C, intermediate; and D, moderate [31]. Metallographic preparation of the samples was carried out according to SFS-EN ISO 17639 [32]. The welds were transversely sectioned at the middle of the joint length, and polished and etched using a 2% Nital solution. Macrographs of the weld cross sections were taken for inspection of penetration, defects, and dimensions and shape of the fusion zone and HAZ (heat affected zone).

3. Results

3.1. Effect of Beam Inclination Angle α

To study the effect of beam inclination angle α on the morphology/geometry of the weld, all other process parameters were kept constant. The beam was positioned 0.5 mm above the joint plane on the flange and focused 2 mm below the surface of the material. Focal point diameters on the surface were 0.82 mm, 1.00 mm and 1.61 mm for the 200 µm, 300 µm and 600 µm process fibers, respectively. The cross sections of the welds are shown in Figure 3.

It can be seen in Figure 3 that the penetration depth (measured from top of the weld) and the length of the joint fusion along the intersection decreased as the inclination angle increased. It can also be noticed that the penetration depth and area of the fusion zone correlate with the energy density of the beam. A full penetration weld was obtained only with the 200 µm process fiber and 6° inclination angle. All of the joints followed the axis of beam propagation. Averaged dimensions from three welds produced with each inclination angle are shown in Table 4.

Table 4. Effect of fiber diameter on the weld dimensions.

Fiber Diameter [µm]	Penetration Depth [mm]	Bead Width [mm]	Fusion Zone [mm^2]	HAZ Area [mm^2]	Depth to Width Ratio	Max Hardness HV5 [FZ [1]/HAZ]
200	8.7	2.3	13.2	6.5	4.0	386/373
300	7.8	2.4	12.6	6.0	3.3	392/359
600	5.6	2.7	12.0	5.5	2.0	393/365

[1] FZ = fusion zone.

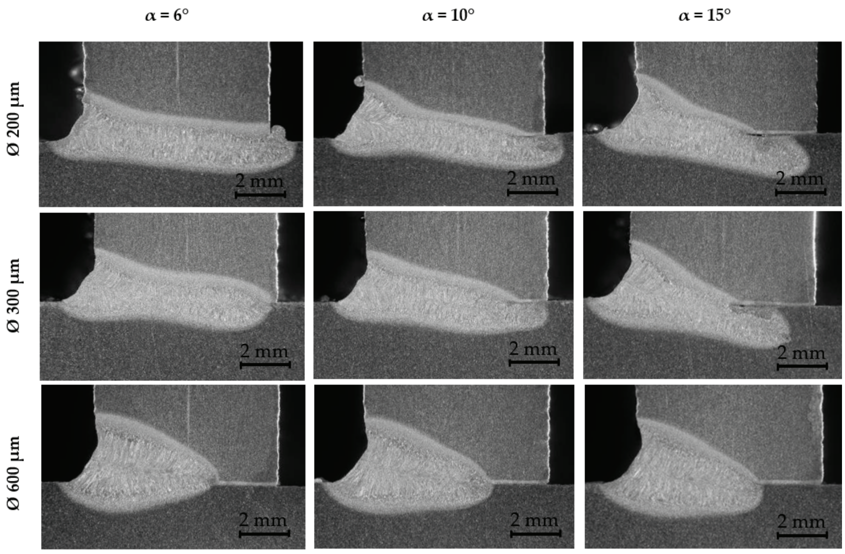


Figure 3. Macrographs of weld samples at different beam inclination angles: AH36, t = 8 mm, P_L = 6 kW, v_w = 1.25 m/min, beam offset from flange 0.5 mm, F_{PP} = −2 mm.

3.2. Effect of Beam Offset from the Flange

The effect of the beam offset from the flange was studied only with 300 µm and 600 µm process fibers. Based on the very narrow bead width produced earlier with the 200 µm process fiber and an assumption that the weld width largely determines the tolerance limits, the 200 µm process fiber was not included in the experiments. The laser power needed for full penetration was first calculated using the Power Factor Model developed by Suder et al. [23] and subsequently determined experimentally. The calculated values exceeded the real power requirement by at least 30% (less than 8 kW vs. 9.7 kW, F_{PP} −2 mm, beam Ø on surface 1.0 mm; 10 kW vs. 13 kW, F_{PP} −2 mm, beam Ø on surface 1.6 mm). Macrographs showing beam offsets from 0.5 mm to 2.0 mm are presented in Figure 4.

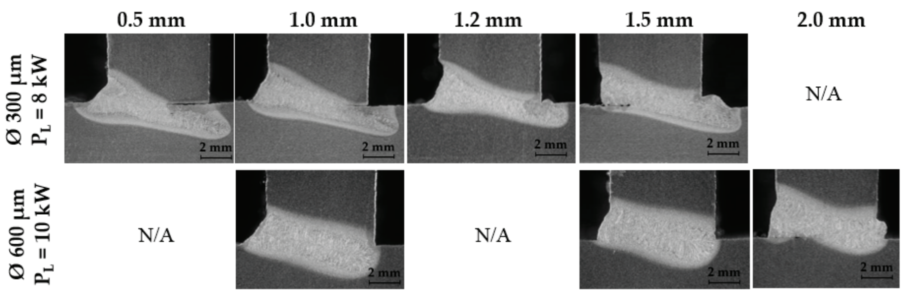


Figure 4. Macrographs of weld cross-sections when beam position from the flange was varied: material = AH36, t = 8 mm, v_w = 1.25 m/min, F_{PP} = −2 mm, α = 15°.

As shown in Figure 4, despite similar width of weld bead, there was a significant difference in the geometry of the fusion area. Welds produced with the 300 µm process fiber had a deep and narrow profile with a slightly wider top typical of high power laser welds. The setup with the 600 µm process fiber produced welds that were wide throughout the whole fusion area, resulting in a more acceptable weld profile for a T-joint.

3.3. Effect of Focal Point Position

Negative defocusing was used to study whether decrease in beam density at the workpiece surface has a favorable effect on the formation of the weld bead. The influence of focal point position on the weld profile was investigated by changing the defocusing distance in steps of 2 mm. Beam offset from the flange was selected as 1 mm and 1.5 mm (for the 300 μm and 600 μm setups, respectively) to increase the likelihood of full penetration. The focal point was moved along the beam propagation direction inside the material in 2 mm steps. Figure 5 shows cross-sectional macrographs of the welds produced.

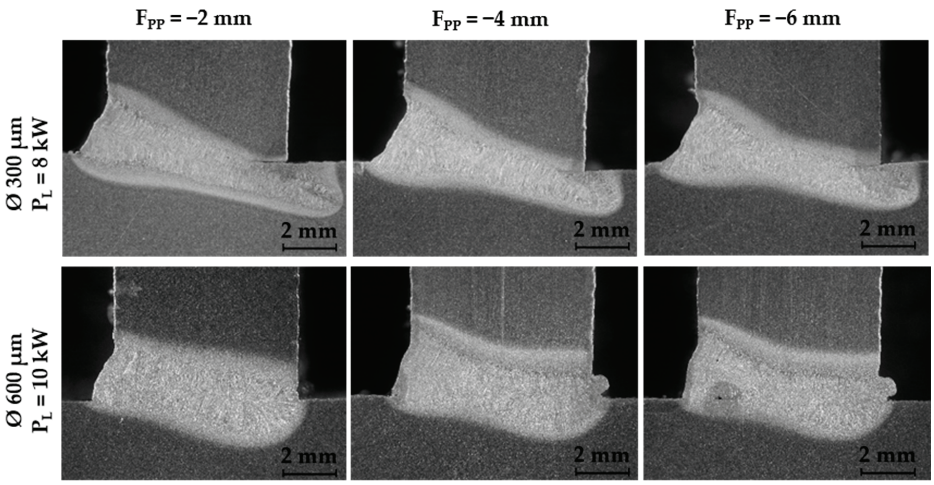


Figure 5. Weld profiles at various focal point positions: AH36, t = 8 mm, v_w = 1.25 m/min, beam offset from flange 1.0 mm (up) and 1.5 mm (down), $\alpha = 15°$.

It can be seen from the images presented in Figure 5 that decreasing the focal point position leads to a slight decrease in penetration. F_{PP} −4 mm resulted in full penetration in the set-up with the 600 μm process fiber, while none of the welds produced with the 300 μm fiber had complete penetration at the weld root.

4. Discussion

4.1. Geometry of the Welds

The purpose of this study was to investigate geometrical differences in welds produced with three different beam delivery fibers and to determine the effect of process parameters on T-joint welds. Thirty welds were produced, evaluated, and their cross-sections analyzed. The acceptance criteria in visual inspection were smooth and plain face and root sides of the weld seam, lack of spatter, cracks or other defects listed in the Standard EN ISO 13919-1, and full visible penetration on the root side. Cracks or porosity were not present, qualifying the welds for class C of ISO 13919-1. Obvious undercut and lack of fusion produced by an inappropriately positioned beam or a lack of laser power were causes of rejection.

The width of the weld fusion zone determines the largest acceptable inclination angle for producing full penetration at a given web thickness. It can be seen in Figure 3 that compared to the other set-ups studied, the process fiber with a core diameter 600 μm was least sensitive to increase of α. However, at given thickness of 8 mm, α = 6° produced the largest weld throat in all set-ups, regardless of the diameter of the beam, since the keyhole formed strictly along the axis of beam propagation. Figure 6 illustrates the effect of beam inclination angle on melt distribution relative to the middle axis of the joint.

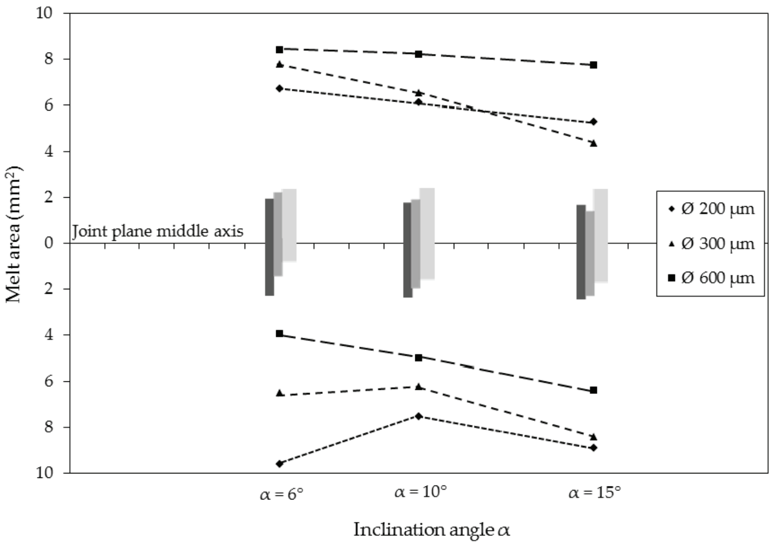


Figure 6. Proportions of the weld and melt area distribution differences at three inclination angles tested. AH36, t = 8 mm, P_L = 6 kW, v_w = 1.25 m/min, F_{PP} = −2 mm.

Figure 6 shows the size of the melt area above and below the middle axis of the joint of the welds presented earlier in Figure 3. The bars illustrate the proportions of the melt area above (web) and below (flange) the joint plane, and the lines show the area of the melt. Process fibers with core diameters of 200 μm and 300 μm produced welds with similar properties: the melt area decreased with increase of inclination angle. The 600 μm diameter process fiber produced welds in which the melt area increased while simultaneously keeping the same proportions of the fusion zone above and below the joint axis. The fiber producing the largest focal point diameter was least sensitive to change of inclination angle.

From an engineering point of view, beam offset is an important parameter affecting the weld quality of fillet welds, where joint bridging ability and ensuring complete fusion are more important than the penetration depth itself. As can be observed in Figure 4, tolerance to beam offset is also determined by the width of the weld. An inclination angle of 15° was chosen over two smaller angles tested based on the width of the weld bead and possible accessibility restrictions of the welding head. Optimal offsets for acceptable top bead and full fusion at the root are: 1.0 mm with the 300 μm transfer fiber, and, 1.0 mm and 1.5 mm with the 600 μm transfer fiber. The diameters of the beams on the surface were 1.0 mm and 1.6 mm, respectively.

When the 300 μm fiber was used, deviation to either side from the 1.0 mm offset produced either lack of fusion at the root or undercut and lack of penetration at the face of the weld. Due to the small width of the weld/fusion zone, higher offset resulted in formation of severe undercut on the top of the weld, while part of the melt was pushed through the weld root. The transfer fiber with 600 μm core diameter had a wider positioning tolerance window because the width of the weld throughout the fusion area is also wider. All of the welds produced with the 600 μm process fiber had a smooth bead and root sides, complete penetration, and class B quality according to EN-ISO 13919-1. It seems that a change in the keyhole process, noticed earlier by [14], can be seen in the case of fillet welds in low alloyed steel. It is logical that power density has an effect on the process mechanism while still producing weld shape that is similar but wider than in the case of higher power density.

The focal point position has the same effect on T-joints as any other weld. Comparing the setups studied, an insignificant increase in bead width in correlation with an increase in beam dimension on the surface of material was noticed. F_{PP} of −2 mm produced welds with a larger weld toe radius than F_{PP} −6 mm. When F_{PP} was positioned at −4 mm, that is, at half of the thickness of the web, the setup produced fully fused welds lacking porosity or other defects on both sides of the joint.

4.2. Application of Specific Point Energy to Welding of T-Joints

Traditionally, the depth of penetration has been characterized through the concept of heat input, also called line energy, which describes the energy available for producing the weld through the relationship of available laser power and welding speed. E_{SP} also considers the diameter of the beam on the surface of the specimen and therefore provides higher accuracy in definition of the penetration depth and weld geometry [23]. Suder and Williams [22] have shown that, in the case of bead-on-plate welds, the penetration depth is defined by power density and specific point energy, and the width of the weld by interaction time, regardless of the optical setup used. T-joint fillet welds follow the same analytical model regarding the penetration depth as bead-on-plate welds; in this work, however, there was a deviation at larger beam diameters produced with the 600 µm process fiber. The relationship between E_{SP} and penetration depth for all three setups is summarized in Figure 7.

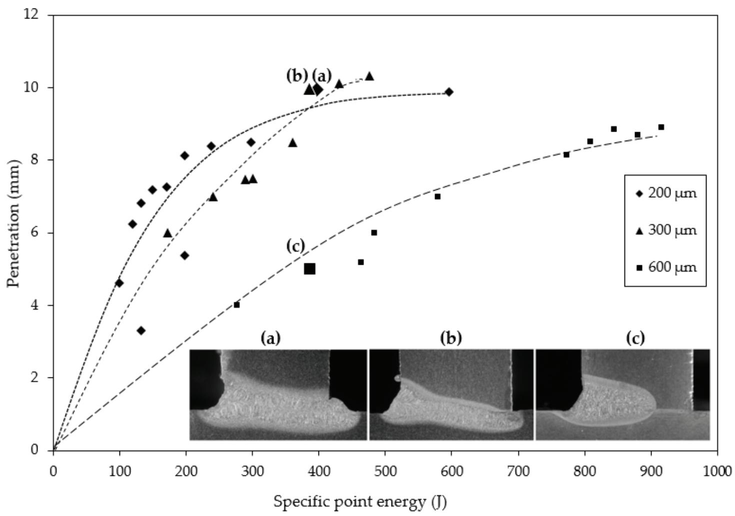


Figure 7. Penetration depth plotted as a function of specific point energy. E_{SP} values of the three welds shown: (▲a) 396 J; (◆b) 384 J; and (■c) 386 J.

Figure 7 shows curves for penetration depth produced with each of the process fibers and macrographs of three welds obtained at similar E_{SP} using different process fibers. Beam diameters on the surface of the welds shown in Figure 7 were 0.82 mm, 1.00 mm and 1.61 mm (F_{PP} −2 mm). The following laser power and welding speed combinations were used: (a) P_L = 6 kW, v_w = 0.75 m/min; (b) P_L = 8 kW, v_w = 1.25 m/min; and (c) P_L = 4 kW, v_w = 1 m/min. Welds (a) and (b) both had penetration depths close to 10 mm, when measured from the top of the bead, thus exceeding the thickness of the material, while weld (c) had only partial penetration. At similar E_{SP}, the 200 µm process fiber produced the weld with the deepest penetration and largest melt area (a). Full penetration was not obtained with the 300 μm process fiber despite sufficient penetration depth, and the weld produced with the 600 μm fiber was noticeably shallower.

It is known that the diameter of the beam governs the dimensions of the keyhole, which in turn define the depth and width of the weld. As expected, beams with smaller diameters produced deeper penetrations at any given E_{SP}. Within each setup, it can be seen that an increase in E_{SP} also increases the penetration depth, but comparison of all three setups shows that the power density of the beam has a more pronounced effect on the morphology of the weld than E_{SP}. A possible explanation for this might be that the heat conduction in T-joints is different than in butt joints or bead on plate joints. Distribution of energy over a larger area leads to a slight decrease in molten area and reduced penetration depth. The power density of the beam determines the depth of the weld, while the width of the weld is determined by the diameter of the focused beam on the surface of the specimen.

4.3. Optimal Welding Conditions for T-Joint

The effects of beam inclination angle, beam offset from the flange and the focal point position relative to the surface of the material were studied to gain insight into the applicability of each setup under industrial conditions. Table 5 summarizes the findings.

Table 5. Acceptable limits for beam positioning for producing full penetration.

Parameter	200 μm Process Fiber	300 μm Process Fiber	600 μm Process Fiber
α	6°	6°	6°; 10°
Beam offset	1 mm	1 mm	1−1.5 mm
F_{PP}	−4 mm	−4 mm	−2–−6 mm

The optimal parameters for all set-ups were inclination angle 6°, beam offset from the flange 1 mm, and focal point position −4 mm below the surface of the material. In all of the setups, the axis of the weld was aligned along the direction of the beam propagation. For this reason, when the beam was aimed past the root of the joint, the formed molten pool did not follow the joint plane, resulting in a lack of fusion at the back of the weld. However, the applicability of a beam inclination angle of 6° in industrial applications may be limited because of a danger of collision of the laser welding head while maneuvering in restricted space, especially in situations where the incident beam side of the flange exceeds the focal length of the laser.

From the industrial point of view, the most versatile solution for T-joints of the three process fibers tested would be the fiber with a core diameter of 600 μm. This setup produced top beads superior in quality to the two other setups studied. The welds made with the 200 μm and 300 μm process fibers were deep yet extremely narrow at the deepest section of the weld and prone to undercut at the surface. A setup with a 600 μm fiber results in a more stable process that has a greater tolerance for beam displacement and smaller probability for seam imperfections.

5. Conclusions

The present work reported welding of single-sided T-joints of 8 mm thick AH36 shipbuilding steel with three optical setups using process fibers with core diameters of 200 μm, 300 μm and 600 μm. The current study found that:

(1) Full fusion in one welding pass was produced with all three process fibers studied.

(2) Penetration depth and width of the weld both primarily depend on the beam diameter. The parameter with the greatest influence on the depth of the weld is the power density of the beam, while the width of the weld is determined by the diameter of the focused beam. The width of the weld bead only has a minor correlation to the diameter of the beam on the surface.

(3) Smaller spot sizes provide an advantage in penetration depth at the same welding speed and power but are prone to producing undercuts. Due to the narrowness of the weld, the positioning of the beam has to be extremely accurate to avoid the weld missing the root of the joint.
(4) Welds produced with 600 μm process fiber were less prone to undercut formation and had more favorable shape of the weld toe than welds produced with 200 μm and 300 μm process fibers.
(5) Process fiber with core diameter 600 μm produced welds with the highest quality and was least sensitive to changes in beam positioning.
(6) Using beam delivery fibers with larger core diameters has a favorable effect on achieving full fusion in T-joints. Reduced energy density on surface increases the width of the weld throughout the penetration and produces smoother junctions of weld bead and base material.

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