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THE EFFECT OF SHIELDING GAS FEEDING METHOD IN LASER WELDING OF STEEL

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1 INTRODUCTION

Laser welding is an efficient joining method for steel and other metals. It has numerous applications in welding fabricating industry and new applications are under research. High power lasers can be used for welding and cutting thick section materials. This makes single pass keyhole welding competitive with multi-pass arc welding (Salminen & Lappalainen & Purtonen, 2013, p. 331-332). One of the most important developments in laser welding is multi-kilowatt fiber laser. The beam quality of fiber laser does not decrease significantly when increasing laser power. That combined to low life time costs and the ability to use optical fibers for delivering the beam makes fiber laser an ideal laser beam source for the needs of welding fabricating industry. (Veerhaeghe & Hilton, 2005, p. 192.)

Gas shielding plays an important role in laser welding phenomena. It does not only provide protection against oxidation but it has an effect in beam absorption and thus welds penetration. (Quintino et al., 2011, p. 399.) In order to obtain proper quality welds gas shielding should be sufficient and optimal (Shin & Nakata, 2010, p. 36; Kuo & Lin, 2007, p. 226). Different shielding gas feeding methods have been studied in numerous research articles. The most commonly used seems to be a side jet directed in the keyhole. Highly reactive materials such as titanium and non-ferrous alloys may require better shielding which leads to larger shielding arrangements such as environmental shielding (Shirvan & Choquet & Nilsson, 2012, p. 1-8; Wang et al., 2007, p. 382-384.) Mild steels are, on the other hand, less reactive and they are occasionally even welded without shielding (Lappalainen & Purtonen & Salminen, 2012, p. 260-263). Since shielding gas itself and the way it is fed to the process seems to have an effect in the phenomena, it could be considered as an important part of the process. The way these feeding methods affect the phenomena has yet to been compared thoroughly in literature.

The goal of this literature survey is to study and compare the effects of different feeding methods in laser welding with fiber laser. The focus of this study is to analyse which feeding methods shield the melt pool properly. Characteristics of the feeding methods are introduced in order to understand the reasons for the arrangements of each shielding method. By understanding these characteristics it is possible to compare the methods to each other. How these characteristics affect in shielding of the weld pool from ambient air is an important objective of this study. Another thing is to discover the way it affects in the metal vapor plume formation above the keyhole. This is because the plume affects to the absorption of the laser beam. Different shielding gases are introduced due to their various effects in keyhole formation and gas flow dynamics.

Studied material is limited to low alloy steels because those are the most common materials in welded steel structures. Therefore effective laser welding in these structures is important. Laser source considered in this survey is fiber laser. It is a relatively new laser beam source comparing to other lasers capable to deliver multi-kilowatt power such as CO_2- or Nd:YAG lasers. It has a high quality beam and small size of the laser device when compared to CO_2 or Nd:YAG lasers. Shielding arrangement is top shielding in this study. Root shielding methods are not discussed.

2 METHODS

In this study the research method is a literature survey. Welding research articles provide necessary information of the phenomena. The effect of shielding gas has been addressed by many authors. Articles about laser welding are studied for getting useful information about shielding methods. This was possible even when gas shielding itself was not studied because in most articles shielding method was mentioned. If the weld quality proved to be excellent, shielding conditions were sufficient. In some of the articles feeding of shielding gas in welding with fiber lasers has been studied. In majority of the cases the process studied was keyhole welding as it enables joining of thick section materials (Steen & Mazumber, 2010, p. 203).

In most of the articles studied in this research welding was carried out using fiber, Nd:YAG or CO_2 laser. Articles regarding to CO_2 and Nd:YAG laser welding were also used in this survey because those usually presented a shielding method. These articles provided research information which is useful when finding optimal shielding methods for welding with fiber laser. Beam quality and other laser characteristics have vary in different laser types but this does not seem to have a great effect in shielding against oxidation. Thus research articles about other lasers are relevant as well. When investigating the effect of gas shielding to plasma or metal vapor formation, CO_2 lasers were looked at only briefly as the wavelength of the beam is a magnitude higher than that of fiber laser (Quintino et al., 2007, p. 1233). The wavelength has a great effect in shielding gas ionization (Quintino et al., 2011, p. 399). Plasma formation is found to be little or non-existent with Nd:YAG and fiber lasers whereas CO_2 lasers form plasma (Kaplan & Wiklund, 2009, p. 295; Katayama & Kawahito & Mizutani, 2007, p. 267). There is however a metal vapor plume formed above the keyhole which may defocus the beam with all lasers (Quintino et al., 2011, p. 399). Removing this plume will enhance welding results (Katayama et al., 2007, p. 267). Due to the need of only metal vapor control articles about fiber lasers were used always when possible.

Materials studied were not only low alloy steels. There is a lot of information of gas shielding in use of magnesium alloys or aluminium as also welding of galvanized steel or stainless steel. These articles were however not completely used in literature survey because other materials may demand different shielding conditions. However, these articles usually presented a shielding method. Gas shielding is very important when welding for example stainless steels because full shielding is required in order to achieve bright seams (Patschger et al., 2011, p. 46). The results of weld quality are therefore important for welding of low alloy steels as well.

Flow models give good information about shielding gas behavior. Computational fluid dynamic (CFD) models are useful since gas flow can be difficult to estimate. CFD models alongside heat transfer models give strong basics for gas shielding (Patschger et al., 2011, p. 55; Tani et al. 2007, p. 905). Welding speed has an important role in this phenomenon as well (Patschger et al., 2011, p. 54). The effect of welding speed is, however, not evaluated with each feeding method. This is because it does not affect the geometry of the feeding method. Since this work is a literature study no experiments were performed.

3 LITERATURE SURVEY

This chapter gives information about welding with high power fiber lasers and shielding of the weld pool. -The chapter begins with the principles of gas shielding in laser welding. The main focus is in different methods of feeding the shielding gas. The basics of fiber lasers and laser welding are introduced first. Laser welding has significant differences from traditional arc welding processes and therefore principles of gas shielding are different. The main differences are in the shape of the weld pool and formation of plasma or metal vapor plume above the weld pool. Therefore characteristics of gas shielding in laser welding of low alloy steel are introduced before gas shielding feeding methods.

Some basic welding metallurgy of steel is introduced due to its fundamental role in weld pool protection. Heat conduction and computational fluid dynamic models (CFD) are also briefly introduced. This is because they are used in several articles to study gas flow which is difficult to measure experimentally. Heat conduction is generally an important factor in welding since controlling the heat distribution affects formation of distortions and the shielding zone. These factors should give an idea why gas shielding is carried out the way it is in several research articles and why shielding sometimes fails.

3.1 The basics of fiber laser

Fiber laser is a solid state laser which has risen interest in welding and cutting of thick section materials. Laser beam of the fiber laser is generated and can be transported via optical fiber. This is an easy way to transport the beam when compared to using a complex and fragile system of mirrors and lenses as in case of CO_2 laser. Fiber lasers have made processing of thick section materials easier. Increase in the maximum laser power of a single fiber laser source does not significantly decrease beam quality of it. Maximum laser power of a single fiber laser can be as high as 50 kW (Vänskä & Purtonen & Salminen, 2012, p. 15). The focusability of the beam is good, which is important because a small focal point size means high power density of it. Fiber laser has a wavelength of 1070 nm when using ytterbium doped core. This means good absorption in steel. (Quintino et al., 2007, p. 1232-1233.)

An advantage of fiber laser is its small size of the laser device itself compared to CO_2 or Nd:YAG lasers. Maintenance costs for fiber laser are small or non-existent due to the diode laser pumping technology used for producing the laser beam. The floor space required and mobility of the laser device are important benefits in addition to high brightness of the laser beam. (Veerhaeghe & Hilton, 2005, p. 192.)

A single mode fiber laser consists of a fiber in which the beam is generated. This fiber has a core doped with low levels of rare earth which forms the lasing medium. The laser beam is generated by laser diode pumping which makes the doped core emit photons at a specific wavelength. Laser power is increased by connecting several single mode fiber lasers into a multimode laser. Figure 1 presents a laser unit which consists of 200 W single mode fiber lasers. (Veerhaeghe & Hilton, 2005, p. 188-189.)

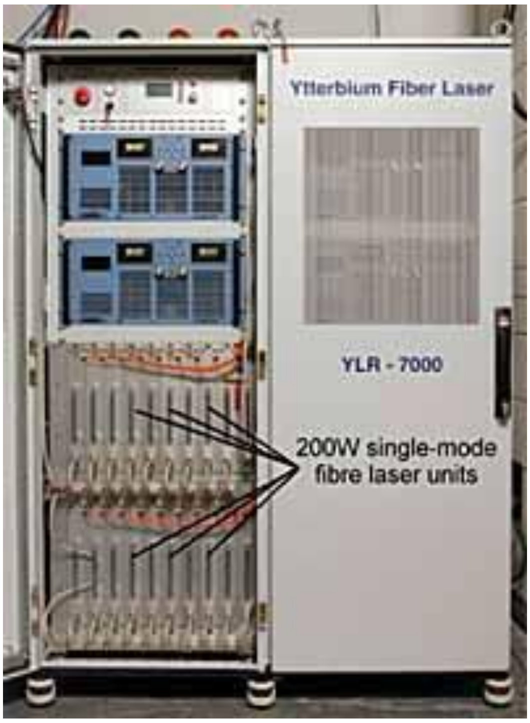

Figure 1. A multimode fiber laser unit (Veerhaeghe & Hilton, 2005, p. 190).

3.2 Laser welding

There are two operating modes in laser welding. In the first one a beam melts the material creating a weld pool. This is called a conduction limited mode. The second mode is deep penetration mode. Laser beam is focused in the welded material and at a sufficient power density a cavity is generated in the material around the laser beam due to material boiling and evaporating. This cavity is called keyhole and therefore the process is called keyhole welding and it is a highly productive process making it possible to use a single pass even when welding thick section materials. (Steen & Mazumber, 2010, p. 203.)

Once the keyhole is generated it is stabilized by the evaporating gas flow inside of it. The pressure generated by this gas flow and the right welding speed are required to maintain a keyhole. CO formed by carbon and oxygen in the material seems to have great effect in maintaining the keyhole (Zhao et al., 2009, p. 765). The balance between surface tension pressure of the weld pool and vapor pressure prevent the keyhole from collapsing (Sibillano et al., 2007, p. 367). Weld pool dynamics are formed by so called Marangoni flow. This flow effects formatting weld bead. Welding speed being too low the keyhole may collapse or at too fast speed it may not fully penetrate the material. Full penetration is not however always required. Once a laser beam is focused in the welded material the beam absorptivity can be as low as 3% when welding highly reflective materials. Once a keyhole is generated absorptivity can reach up to 98 % rapidly. This can be destructive for a welded material because of a high peak in heat input. In some cases the laser power can be lowered once a keyhole is formed. At this point the beam is considered to be almost fully absorbed in the material. High absorptivity is caused due to the beam reflections inside the keyhole. (Steen & Mazumber, 2010, p. 203-204.)

The depth of the weld has a nearly linear relationship with the laser power and it decreases exponentially when welding speed increases (Quintino et al., 2007, p. 1235). Formation of the weld bead is also straight forward. With increasing laser power or decreasing welding speed the top bead width of the weld will increase. Shielding gas being used does not affect to this relationship. (Quintino et al., 2011, p. 400.)

3.2.1 Welding with fiber lasers

Evaporating metal and ionizing gases in the keyhole create a plume over the keyhole. This plume of metal and plasma may cause defocusing of the beam. This affects to stability of the welding process and formatting of the weld bead. In fiber laser welding this is not as great problem as it is when welding with CO_2 lasers. The plume is mainly created by evaporating metal and alloying elements. Plasma created by shielding gas does not seem to have an effect in formation of the plume. This is due to the wavelength of a fiber laser beam which does not ionize the gas. Interaction with the metal vapor or shielding gas and laser beam is even considered to be almost non-existent (Kaplan & Wiklund, 2009, p. 295). A tall plume should however be removed because as it grows bigger it has an effect in weld penetration. This is due to a defocused beam which melts a larger area around the keyhole. A small plume does not seem to have a great effect in defocusing the beam. Removing the plume for example by a fan creates a deeper keyhole due to a properly focused beam. (Katayama & Kawahito & Mizutani, 2010, p.12-13.)

Laser welding has generally been used for welding of thin sheets but since high power fiber lasers entered the market new welding opportunities have emerged. Welding with fiber lasers is highly productive and penetration depth of single pass can be even 30 mm. Full penetration welding of 25 mm thick S355 structural steel is possible by using a 30 kW fiber laser. This improves productivity when compared to traditional multi-pass arc welding. Productivity is measured in arc welding by an amount of a filler material melted. In laser welding there is usually no filler material to melt and therefore the process seems ineffective when as it should be effective. A way of measuring productivity and efficiency is the amount of time it takes to weld a cross section. This way, different processes can be easily compared and a single pass laser welding of thick section materials becomes highly productive. Productivity can be increased even more by using the same laser source for cutting and groove manufacturing as in welding. This is achieved by using different processing optics. Limitations for using laser welding are standard procedures and accepted practices for production to assure a proper weld quality. (Salminen & Lappalainen & Purtonen, 2013, p. 331-332.)

High performance of fiber lasers is due to power and beam quality. High power of fiber laser creates deeper welds. Beam quality enables greater welding speeds. Both have an effect in productivity. (Seefeld & O`Neill, 2007, p. 315-319.) Using a smaller spot size which is an advantage of fiber lasers creates a smaller keyhole. However a small keyhole is more likely to become unstable and therefore will collapse easier. (Geiger & Kägeler & Schmidt, 2008, p. 236.)

3.3 Characteristics of gas shielding in laser welding

The shielding gas used in welding may effect to the plasma formation and that way to shielding of the weld pool. The purpose of gas shielding in welding is to prevent the seam from oxidizing. In laser welding shielding gas has a great affect in weld bead formation. Shielding gas changes the shape of the keyhole when it reacts with melted metal and therefore brings additional energy to the process. This causes changing in the weld surface tension and changes the shape and size of the keyhole. Plasma plume created above the keyhole can defocus the laser beam. (Quintino et al., 2011, p. 399.) Shielding gas should provide laminar gas flow on top of the work piece in order to prevent oxidation. A turbulent flow should therefore be avoided because of ambient air mixing with the shielding gas. This can be affected by using proper shielding gas feeding method. (Salminen & Lehtinen & Harkko, 2008, p. 361-362.)

3.3.1 Gas shielding with fiber lasers

Gas shielding when using a fiber laser has specific requirements. This is because of a smaller keyhole and weld pool. Oxidizing area therefore seems to be smaller. Higher energy density of the focused beam compared to other solid state lasers means higher temperature for the metal vapor. This means that the material oxidizes easier. Higher welding speed means a longer weld pool and longer shielding zone. For welding thicker materials root shielding is also important. It leads to better weld quality and a more stable keyhole. Root shielding is common especially for welding of stainless steels. (Kaplan et al., 2008, p. 790; Salminen & Piili & Purtonen, 2010, p. 1026-1027.)

Shielding gas influences to the form of the weld bead. A wider weld bead means lower penetration and therefore the shape of the weld should be optimized. Argon is an ideal gas for deep penetration welding when compared to helium due to its higher density. Therefore it will blow away the formatting metal vapor more efficiently at the same flow rate. Using 100% helium instead of 100% argon means a significant decrease in penetration depth. When comparing using of argon, helium and CO_2 for shielding, it is shown that adding helium to argon will reduce the penetration depth in deep keyhole regime in which the depth of the keyhole is between eight and ten millimeters. In shallow and medium keyhole regimes which are between one and four millimeters, both argon and helium are effective as shielding gases. Adding CO_2 to argon will enhance the penetration especially in the shallow keyhole but also in the medium keyhole regime. (Quintino et al., 2011, p. 400-403.)

Plume formation with fiber laser is found to be small. Whereas welding with CO_2 laser ionizes argon and nitrogen easier. This creates plasma and shallower weld bead is formed. Plume formation was studied by Katayama et al. at the energy density of 1 MW/mm^2. Interaction between the plume and laser beam was small. (Katayama et al., 2007, p. 267.) Plasma formation is even considered to be impossible in fiber laser welding and shielding gas composition can be compared to TIG welding process. (Scholz & Fieret, 2012, p. 358.)

3.3.2 Welding metallurgy of steel

Most metals are highly reactive with nitrogen, oxygen and hydrogen at elevated temperatures (Reisgen et al., 2010, p. 1401). Air is harmful for molten metals due to its content of oxygen which can cause slag inclusions and nitrogen which can cause brittleness (Shirvan et al., 2012, p. 1).

Nitrogen dissolves in iron and therefore protection against it should be considered. Nitrogen comes from ambient air. The sharp edges of iron nitride provide ideal sites for initial cracks in ferrite matrix. Because of this, ductility and impact toughness of the weld decrease with increasing nitrogen in the weld. Since it is an austenitic stabilizer, it can be added in inert shielding gases. Therefore it is mixed with argon when welding certain types of steels, as duplex stainless steels for example. (Kou, 2003, p. 71-72.)

Oxygen comes to the weld from the air and it oxidizes carbon and other alloying elements. This will modify their prevailing role and have a depressing effect in hardenability. Therefore it has an effect in weld quality by formation of inclusions and loss of alloying elements. Oxygen content increases porosity and therefore it should be minimized (Tsukamoto et al., 2010, p. 623). Another harmful element is hydrogen which comes from moisture or shielding gas. Hydrogen causes hydrogen cracking. (Kou, 2003, p. 73-75.)

3.3.3 Heat conduction in laser welding

Heat conduction in welding is an important factor. Knowing the dimensions of the heat affected zone in welded material is crucial when designing proper shielding conditions. In laser welding this zone is small when compared to arc welding. Nevertheless it requires full shielding until the temperature of the material is less than 200°C. Heat conduction can be two or three dimensional, which effects the cooling time of the weld. This depends on welding speed. In 2-dimensional heat conduction weld cooling time is proportional to quadrature of welding energy whereas in 3-dimensional it is proportional only to the energy used. This means that welding speed being too low cooling time of the weld is longer. This, however, is not dependent of material thickness. For example when welding a 3 mm thick steel sheets using a 1 kW laser power heat transfer turns into 3D conduction at the feeding rate of 43 mm/s. (Patschger et al., 2011, p. 54.) Welding at lower speed is likely to create severe oxidation. This is due to longer time during which a weld pool reacts with ambient air. (Zhang et al., 2007, p. 851.) Karkhin et al. presented a technique for measuring heat distribution in laser welding. The calculated distribution is similar to an actual measurement from the work piece. This concludes that heat conduction can be reliably modeled and taken into account in laser welding. (Karkhin & Homich & Michailov, 2007, p. 21-26.)

3.3.4 Simulation of shielding gas flow

Some studies have been made in order to investigate the shielding gas flow in laser welding. Since it is difficult to measure gas flow, numerical models have been made using CFD models. Comparing of gas velocity vectors provides important information of the gas flow. (Shirvan et al., 2012, p. 2-7.)

Shielding gas densities vary greatly from each other. For example argon is 38 % more dense than air, and helium has 14 % density that of air (Maol ry, 2006, p.78). This has a great influence in shielding gas flow and thus flow model is dependent of the shielding gas being used. Gas density in the shielded area can be simulated using a proper model. Flow simulation provides information of gas density while using different gases, distance from keyhole, flow rate and inclination angle of the nozzle. (Tani et al., 2007, p. 905-907.)

3.4 Different types of shielding gas feeding methods

There are numerous shielding gas feeding methods applied in laser beam welding. Several studies have been carried out to test different feeding methods. The feeding methods presented in this survey are:

1. side nozzle
2. multiple nozzles
3. environmental shielding
4. coaxial feeding
5. lateral feeding

Each one has its own characteristics and applications. Nozzle parameters such as inner diameter and inclination angle are mentioned in addition to process parameters available. Material thickness is also mentioned when necessary.

3.4.1 Side nozzle

A common way of feeding the shielding gas is to use a pipe directed from the welding direction in the welded seam. This is shown in Figure 2. -Quintino et al. studied welding of high strength pipeline steels by using this method. In this study shielding gas was fed through a 5 mm diameter gas nozzle directed 40° from horizontal direction towards the keyhole. The nozzle was in front of the weld as in Figure 2. This arrangement blows away the metal vapor on top of the keyhole. It also prevents the cooling weld from oxidation. This method has successfully been used for austenitic stainless steel at material thickness of 10 mm and flow rate of 15 l/min (Buschenke et al., 2009, p. 34-36). (Quintino et al., 2011, p. 399-400.)

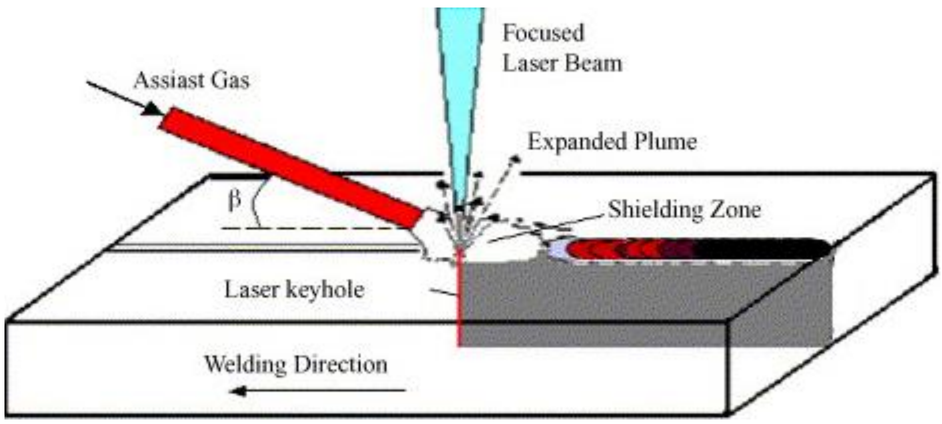

Figure 2. A side nozzle arrangement for gas feeding (Wang et al., 2007, p. 380).

Even though 40° inclination angle is used in many studies, the effect of directing the nozzle has been studied by Wang et al. This has been carried out by using CFD modeling. In order to achieve the longest shielding zone the effect of various parameters: inclination angle, shielding gas and flow rate need to be investigated. The flow rate of the gas plays a significant role since it mostly determines the shielding zone which affects the gas consumption. The inclination angle β, as shown in Figure 2, has a great influence in the length of the shielding zone which is shown in Figure 3. The shielding zone can be defined by measuring its characteristic length which means the distance in which assist gas mass fraction of 0.83 is regular and clear. When inclination angles varied between 15° and 60° from the horizontal direction it is shown that the longest shielding zone with the least gas consumption can be achieved when the inclination angle is 15°. In this case argon was used as a shielding gas. Characteristic length of the shielding zone was 100 mm longer, being 180 mm, than using an inclination angle of 30° while flow rate is 12.5 l/min. When using argon as shielding gas the characteristic length of the shielding zone is longer than with helium gas. Nozzle being used in CFD modeling was 8 mm in diameter. (Wang et al., 2007, p. 382-384.)

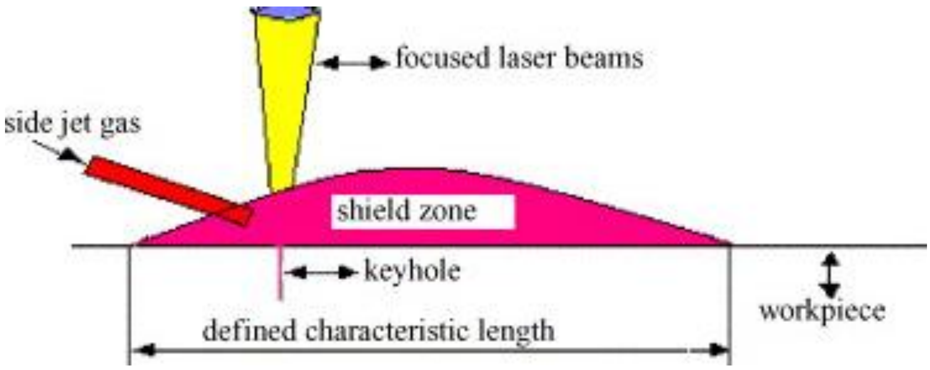

Figure 3. Characteristic length of the shielding zone (Wang et al., 2007, p. 382).

This arrangement has certain limits when it comes to thickness of the welded material. Carbon steel plates with thickness of 16 mm were welded using a 10 kW fiber laser. Inclination angle of the nozzle was 45° and shielding gas 100 % argon. Porosity became an issue in this arrangement. In partially penetrated welds porosity was mainly caused by entrapment of the shielding gas. There was nitrogen, carbon oxide and hydrogen in the weld as well. Nitrogen came from air and hydrogen from the moisture in the air. In fully penetrated weld, bead porosity was mainly caused by nitrogen or carbon oxide. Argon caused minor trapping and was no longer the main cause to porosity. It is assumed that this is caused by lack of root shielding. Without root shielding, air can infiltrate the fusion zone. (Shin & Nakata, 2010, p. 33-36.)

Welds without defects have been obtained using this arrangement for material thickness of 12 mm at the flow rate of 15 l/min. Welded material was S355 mild steel in bead on plate and butt joint configuration. Other welding parameters were optimized. The effect of gas shielding was not studied. These welds only partially penetrated the material, welding depth being 6 mm. (Suder & Williams, 2010, p. 655-657.)

High strength low carbon 780 MPa steel has also been welded successfully in bead on plate configuration. Argon flow rate was 10 l/min via side nozzle in 45° angle. Weld penetration being 4 mm. The experiment was carried out with a 2 kW fiber laser. The welds did not fully penetrate the material. (Liu & Kutsuna & Xu, 2006, p. 563-564.)

Nozzle inclination angle of 25° has been used for welding 3 mm thick Inconel 690 alloy. A nozzle of 4 mm in diameter was placed in front of the beam. Welding configuration was bead on plate with a 2.5 kW Nd:YAG laser. The welds did not fully penetrate the material. It is shown that at this arrangement, argon and nitrogen provide good shielding against oxidation whereas helium does not. This is due to low density of the helium gas. Formation of porosity was the highest with argon and the lowest with nitrogen in this experiment. Flow rate was found to have an effect in porosity. High density gases create porosity at higher flow rates. (Kuo & Lin, 2007, p. 219-220, 226.)

A nozzle with 16 mm diameter has been used for welding of 30 mm thick austenitic stainless steel plates. Full penetration was not achieved in this bead on a plate configuration. Welding phenomena was studied by using laser powers between 5 kW and 26 kW. Weld surface appearance was visually poor with all laser powers. Macrographs showed very little signs of porosity. Shielding gas was fed from behind the weld. This did not provide any protection for the cooling weld. (Katayama et al., 2011b, p. 661-665.)

30 mm thick austenitic stainless steel plates have also been welded in bead on plate configuration by Zhang et al. Welding speed was only 0.3 m/min with a 10 kW fiber laser. Sufficient shielding conditions were achieved by using a nozzle of 20 mm in diameter. Shielding gas flow was 80 l/min. Nozzle was directed from behind of the keyhole. According to high speed camera images there is hardly any oxidation floating in the weld pool. Welding speed is very low, therefore the weld pool has more time to react with the ambient air. This arrangement does not seem to provide proper shielding for cooling weld because weld bead appears oxidized. When compared to a nozzle of 14 mm in diameter and 40 l/min gas flow rate the weld bead is severely oxidized as observed in high speed camera images. The authors found this arrangement to provide poor shielding. (Zhang et al., 2007, p. 851-852.)

MIG/MAG torch can be used for feeding the shielding gas especially in laboratory experiments or with hybrid welding equipment. Sokolov et al used this method in different studies for weld hardness analysis and the influence of the edge roughness level using a high power fiber laser. In both cases the welded material was S355 structural steel in butt joint configuration. Material thickness was 20 millimeters and shielding gas was argon with a flow rate of 20 l/min. The welds did not have critical imperfections. (Sokolov et al., 2011, p. 5128.) & (Sokolov et al., 2012, p. 2066-2070.) MAG torch is however designed for manual arc-welding. At higher welding speeds it cannot protect weld pool from oxidizing. Turbulent flow of the shielding gas is found to inject surrounding air into the weld. This was studied by using Schlieren techniques. (Salminen & Piili & Purtonen, 2010, p. 1026.)

A double shielding nozzle as shown in Figure 4 has been used for welding of 40 mm thick stainless steel plates in butt joint configuration. Welding was carried out by using two passes from both sides. Welding speed was 0.3 and 0.2 m/min with a 10 kW fiber laser. The nozzle consists of an inner gas jet nozzle which is 2 mm in diameter and an outer nozzle which is 20 mm in diameter. Nitrogen was used as a shielding gas at a flow rate of 12 l/min. This type of nozzle is designed to produce deeper penetrations than welding without inner gas jet. The authors found that this arrangement created welds without porosity or other defects. (Zhang et al., 2009, p.691-695.)

Figure 4. A double shielding nozzle in front of the beam (Zhang et al., 2009, p. 691).

The size of the shielding zone has been measured by simulating shielding gas percentage and comparing it to a distance from the keyhole. Tani et al. compared a vertical nozzle with a diameter of 6 mm into inclination angle of 60° from the vertical axis with argon as a shielding gas. Using a vertical nozzle provides full shielding for the molten pool but it does not provide protection for the cooling weld. 60° inclination angle provides better shielding for the cooling weld but there is no area with a presence of 100 % argon. These methods were however not tested in practice. In this study it was suggested that using multiple nozzles or environmental shielding boxes would provide an efficient shielding for welding of highly reactive materials such as titanium. (Tani et al., 2007, s. 905-907.)

3.4.2 Multiple nozzles

Using of multiple nozzles has been studied by Patschger et al. Several nozzles were connected to each other in a way that they provide protection for molten and cooling metal. Pipes are connected to each other one after the other as shown in Figure 5 they are in about 45 ° angles from the horizontal level. This system is placed trailing the laser beam. Shielding gas is fed to the welding process in different nozzles providing protection while the weld is cooling down. Two nozzles are enough for the required shielding when using a sheet thickness of 3 mm and 1 kW laser power. One nozzle provides gas in to the keyhole and the other into the cooling weld. This configuration was used for welding stainless steel. Visual appearance of the weld top face was the most important quality feature. Resulted weld quality was good in this configuration. (Patschger et al., 2011, p. 53-55.)

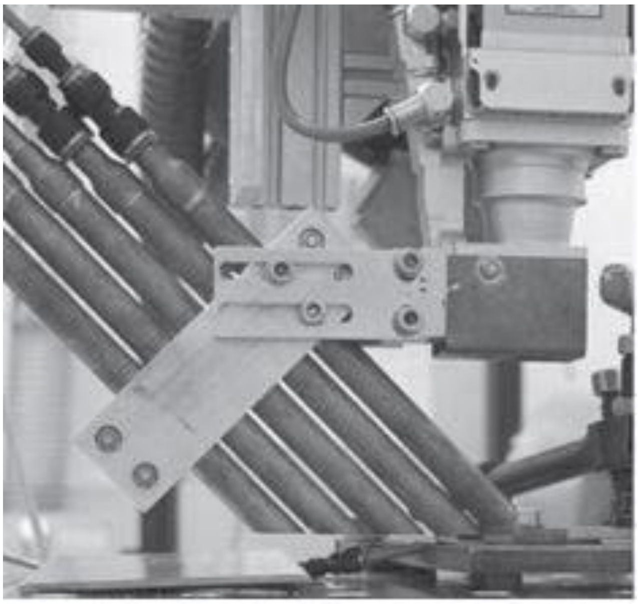

Figure 5. Multiple nozzles for gas feeding (Patschger et al., 2011, p. 54).

In case of heavy spattering as when welding galvanized steel the focusing lens may require better protection and metal vapor plume better control. In this case multiple nozzles can be used from different directions. Mei et al used a side-blown ejection nozzle at an inclination angle of 30° and a coaxial-blown ejection nozzle simultaneously as shown in Figure 6. Side blown nozzle is in front of the laser beam. (Mei et al., 2009, p. 1120-1123.) This set up was also used by Yang et al for welding of galvanized steel sheets. Restraining metal vapor cloud and preventing defect formation due to vaporizing zinc was required. Proper quality welds were achieved. Galvanized sheets have been however welded successfully by using only one nozzle at an inclination angle of 45° (Reisgen et al., 2010, p. 1402). (Yang & Carlson & Kovacevic, 2011, p. 9.)

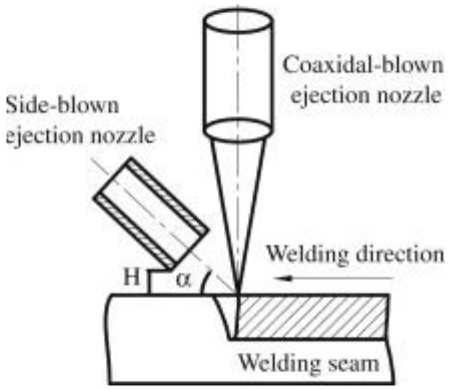

Figure 6. An arrangement for two nozzles (Mei et al., 2009, p. 1121).

3.4.3 Environmental shielding

Reed et al. used an environmentally shielding box as shown in Figure 7 for welding sheet materials of V-Cr-Ti alloys with Nd:YAG laser. This configuration consisted of a box in which gas was fed from both sides. Around the laser head there was a shielding disc through where the shielding gas could flow out of the box. This configuration shielded the weld effectively from the ambient air. However welding large objects requires a larger box which has an effect in fabrication costs. Therefore this arrangement is necessary for highly reactive materials only. (Reed et al., 2000, p. 1206-1209.)

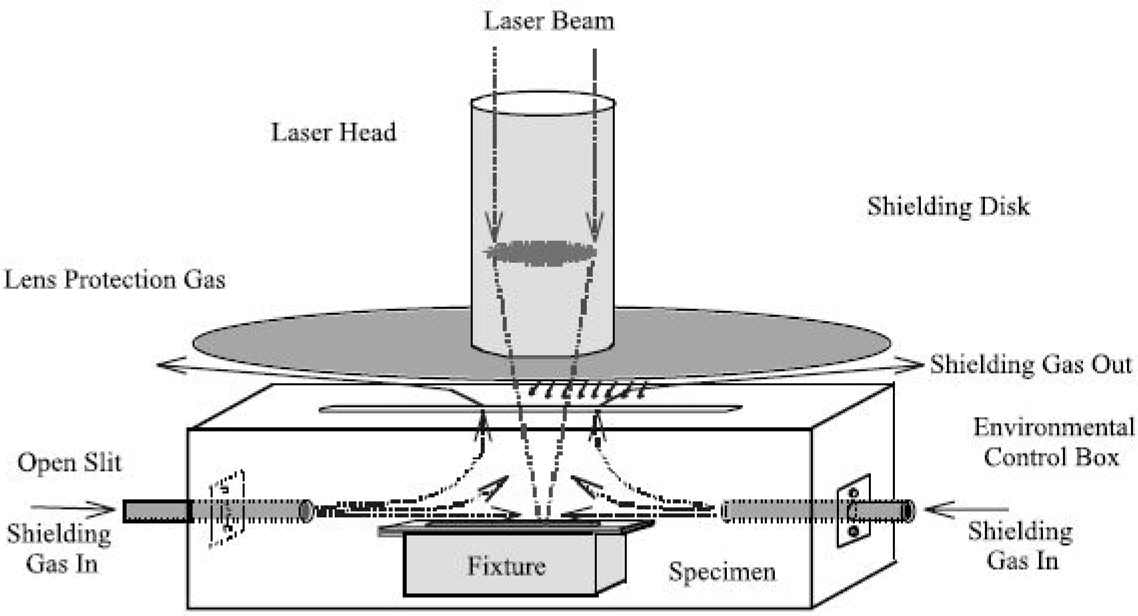

Figure 7. The basic principle of an environmental shielding box (Reed et al., 2000, p. 1208).

Using a plate providing shielding gas after the shielding gas pipe creates a shielding screen on top of the cooling weld. Shielding gas is fed directly in to the process from behind the beam as shown in Figure 8. This configuration was designed for laser welding of highly reactive materials. Thus properly used it should provide full shielding against ambient air. According to a CFD model the gas flows underneath the shielding plate providing a shielding screen and therefore protects the weld while it is cooling down. Shielding in this method was found to be efficient, as it should prevent the weld pool from oxidizing and blow away the metal vapor cloud. Opening in the pipe is critical because it allows laser beam to reach with the shielded area. Gas flow through the shielding plate is only one third of the flow through the main nozzle. Shielding plate also slows down cooling of the weld. Actual welding experiments were not carried out. Therefore the results are based only in computational models. Length of the shielding zone is as long as the plate used. This arrangement was designed for welding of titanium alloys. (Shirvan et al., 2012, p. 2-8.)

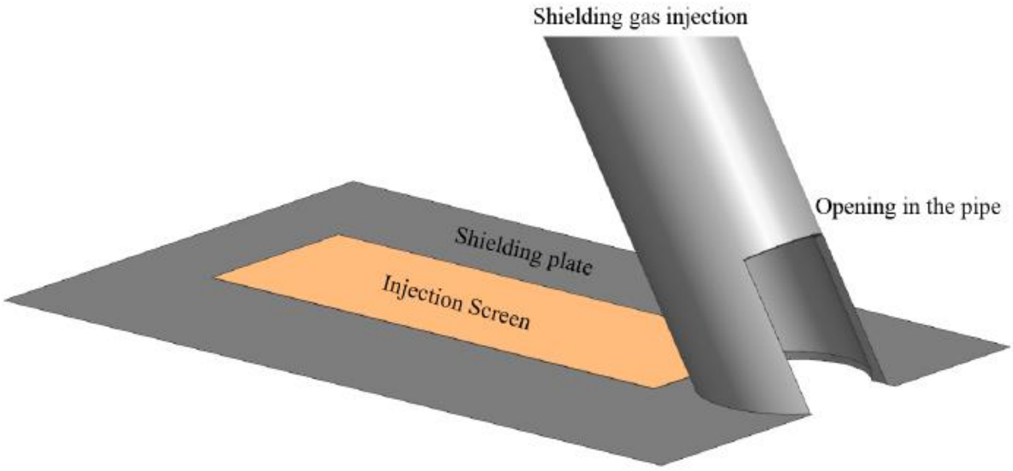

Figure 8. Shielding plate connected to gas feeding pipe (Shirvan et al., 2012, p. 2).

A larger nozzle for feeding shielding gas provides a larger shielding zone. This will lead to much greater gas consumption. Grevey et al. found that using a back extended diffuser providing shielding gas in addition to the main gas nozzle provides sufficient shielding. This leads to similar arrangement as the shielding plate introduced by Shirvan et al. In this case helium is the most suitable gas due to its low density which leads to a low and stable pressure distribution. The shielding area becomes relatively large when compared to using only the main nozzle. Therefore flow rate is lower and low density gases do not evaporate easily as they do when using one nozzle and higher flow rates. (Grevey et al., 2005, p. 647-651.)

Vacuum chamber is one option for environmental shielding. A low vacuum is generated by using rotary pumps. N_2 gas was fed in the vacuum chamber when pressure inside the chamber had decreased to 30 Pa. Pressure inside the chamber is adjusted with the flow rate of this gas. It is shown that under lower speeds the weld penetration is deeper in vacuum when compared to air atmosphere. Weld quality is much worse in air atmosphere than in vacuum. In this case the weld bead has a lot of spatters and appeared oxidized. (Katayama et al., 2011, p. 15-16.) Weld penetration has found to be 4 times greater in vacuum than in air. This is mainly caused by lower plasma. In vacuum there is no ionizing gas. Thus plume is formatted only by evaporating metal. This was investigated by using a 600 W single-mode fiber laser and a 12 kW fiber laser. Welded material was S235 mild steel. (Reisgen & Olschok & Jakobs, 2013, p. 118-122.)

3.4.4 Lateral and coaxial feeding

Ancona et al compared vertical and lateral gas feeding to each other. The vertical feeding consisted of a coaxial focusing head with a conical nozzle. Lateral delivery had a two-pipe nozzle in which the nozzles were on opposite sides of the beam. The pipes are L-shaped and made of copper. The configuration is presented in Figure 9. These feeding methods have been used for welding of 3 mm thick aluminum plates in butt joint configuration. A CO_2 laser was used as a laser source and thus plasma control had a significant effect in the formatting weld bead. The lateral feeding produced deeper welds than the coaxial. Shielding against oxidation was not studied since the focus was in process efficiency. (Ancona et al., 2005, p. 972-977.) The same welding experiments were carried out in bead on plate configuration. In this case the main focus was in shielding instead of process efficiency. Coaxial feeding has proven to be more effective against oxidation whereas lateral feeding produces deeper welds. Helium was used as a shielding gas at flow rates from 40 l/min to 100 l/min. (Sibillano et al., 2006, p. 1039-1051.)

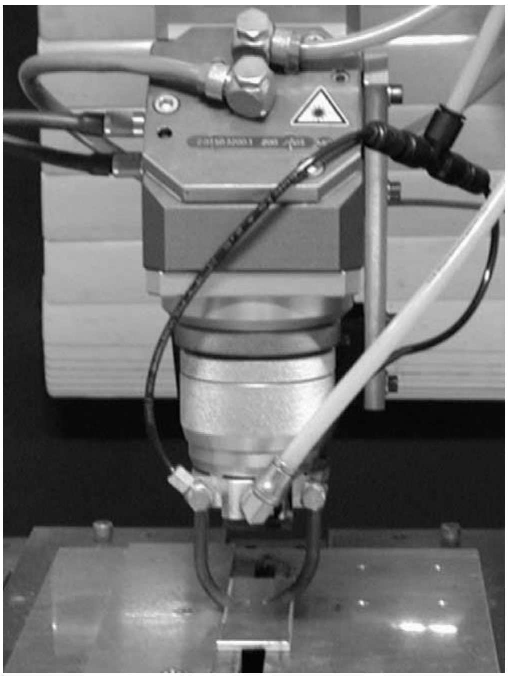

Figure 9. Lateral gas feeding (Ancona et al., 2005, p. 972).

Shielding gas feeding from the lateral direction has also been studied by Patschger et al. This method provides shielding gas alongside the weld. It does not trail the beam, therefore the entire joint is shielded. Lateral supply of the shielding gas provides good metal vapor control and an even weld seam can be achieved. Gas consumption is very high but high quality welds were achieved. In this case it was 60 l/min for welding of 3 mm thick stainless steel plates. (Patschger et al., 2011, p. 53-55.)

3.5 Laser welding without gas shielding

When welding without gas shielding, porosity is likely to become an issue because of nitrogen and hydrogen coming from the ambient air. This happens when root shielding is not carried out properly and therefore air can infiltrate in the molten metal through an open keyhole. In most of the cases porosity is however caused by shielding gas trapping in the fusion zone. This is caused by an unstable keyhole. (Shin & Nakata, 2010, p. 36.) Too low welding speed has a remarkable effect in porosity formation (Kawahito & Mizutani & Katayama, 2007, p. 12). However in laser welding deeper penetrations have been obtained as well in air than in 100% argon shielding. Presence of oxygen creates a wider weld bead than with argon shielding gas. (Patschger et al., 2011, p. 53.) A small amount or air in shielding gas is sufficient to create deeper penetration welds (Zhao et al., 2011, p. 172-173). In order to control the plume on top of the keyhole a small micro-cross-jet can be used to blow compressed air above the keyhole. In this case shielding gas is not used. (Eriksson & Powell & Kaplan, 2011, p. 636.)

Proper quality welds were obtained with S355 structural steel plates in a butt joint configuration. Quality was evaluated visually. Top and root bead were among evaluated quality features. Bead on plate welds had better quality. This study indicates that weld quality is decreasing with increasing welding speed and welding parameters in bead on plate welds were not suitable for butt joints. (Lappalainen & Purtonen & Salminen, 2012, p. 260-263.)

6 mm thick S355 plates have been welded in butt joint configuration without shielding gas. Weld quality was found to be acceptable. Quality was evaluated visually from cross sections of the welds. Full penetration was achieved by using a 5 kW fiber laser. Shielding gas was used in part of the welds. This did not have an effect in penetration in this experiment. Lack of penetration occurred at different laser powers regardless of shielding gas. When shielding gas was used, it was argon fed through a copper side nozzle at a flow rate of 15 l/min. (Salminen & Fellman, 2007, p.418-424.)

4 RESULTS

In the previous chapter it is shown that weld pool shielding requirements are dependent on heat conductivity, shielding gas flow rate and gas nozzle inclination angle and feeding method. Heat conductivity depends on welding speed, material thickness, material itself and laser power. Different shielding gas feeding methods are presented in Table 1. After a literature review it is possible to find out the characteristics of these methods. In this research shielding phenomena is evaluated in five parts: characteristic length of the shielding zone, material thickness, setup for the feeding method, accessibility and gas consumption.

Characteristic length of the shielding zone is the area in which gas mass fraction is 0.83. Within this area shielding is sufficient for welding of low alloy steel. Small shielding zone is less than 80 mm, medium shielding zone is between 80 mm and 180 mm and large shielding zone is more than 180 mm long. Thin sheets are less than 3 mm thick, medium sections are between 3 mm and 6 mm, thick section materials are more than 6 mm thick. Accessibility is defined by the space that the feeding method requires in order to function properly. It is compared between different feeding methods. Gas consumption is measured by gas flow rate which is liters per minute. Nozzle diameter has significant influence in it. Small gas consumption is less than 20 l/min, medium gas consumption is between 20 l/min and 40 l/min, large gas consumption is more than 40 l/min.

One nozzle method has been found to be suitable from thin sheets to thick sections, depending on inclination angle of the nozzle and gas flow. This arrangement provides good metal vapor control at all inclination angles but the longest shielding zone is achieved at the inclination angle of 15°. Increased nozzle diameter and gas flow provides a larger shielding area but it leads to higher gas consumption. One nozzle can be directed in the keyhole in a way that it is possible to produce deeper penetration welds. By using a double nozzle material thickness can be even up to 40 mm. This requires two passes from both sides of the work piece. In case of coaxial direction of the nozzle, thickness of the welded material is limited to the thin sheets. This is due to gas density distribution studied by Tani et al. MIG/MAG torch has also been used to provide shielding gas in laser welding. This method cannot be considered as an ideal for such a purpose, mostly due to turbulent flow of the gas.

Multiple nozzles provide as long shielding zone as there are nozzles connected. For welding thicker materials multiple nozzles should be considered to provide more secure coverage for the cooling weld. Gas consumption is easily adjustable in this arrangement because shielding gas is fed separately into each nozzle. This method requires more space around it than one nozzle. Due to this accessibility to the joint can be limited.

Table 1. Characteristics of different shielding gas feeding methods

Method	**Shielding zone characteristic length**	**Material thickness**	**Setup**	**Accessibility**	**Gas consumption**
One nozzle	medium	from thin to thick section	15 °	medium	from small to large
One nozzle	small	thin sheets	60 °	large	small
Multiple nozzles	large	thick section	two or more	small	from small to large
Lateral supply	small	thin sheets	front and back sides	medium	large

Lateral supply created by two nozzles is suitable for thin sheets. It provides sufficient metal vapor control but length of the shielding zone is not great. Gas consumption is adjustable. Increasing gas flow does not have a significant effect in shielding zone. This is because of the nozzle setup. Shielding gas flow was actually the highest by using this method. Both methods presented by Ancona et al and Patschger et al. had a large gas consumption. Environmental shielding is not necessary for welding of low alloy steel. It would only increase manufacturing costs and not the quality of the weld. Sufficient shielding can be obtained with the methods presented in Table 1. Acceptable quality welds have been obtained even without shielding gas.

When using only one nozzle it is shown by Wang et al. that the best coverage area is achieved when nozzle inclination angle is 15°. This is because of the continuous gas flow on top of the work piece. An inclination angle of 60° has better accessibility than 15° angle, whereas a vertical nozzle is the best from this point of view. Multiple nozzles can be connected to each other and therefore the range of shielding areas is larger than with one nozzle. This method could be considered ideal for thick section materials. Providing shielding gas from different directions offers an option for controlling the process as in case of welding of galvanized steels. A vertical gas delivery offers the best accessibility but at the cost of shielding zone as studied by Tani et al. When mounted into a robot arm with focusing optics this method could provide flexibility for laser welding of thin material. Lateral feeding had been studied by only two authors. It provides proper metal vapor control but shielding against oxidation requires a significant gas flow even with thin materials.

5 DISCUSSION

It found out to be difficult to measure weld quality by studying research articles. Quality features were on many occasions not defined. Therefore evaluating weld oxidation due to insufficient shielding was difficult. The effect of shielding gas feeding has been studied by many authors. The actual phenomenon is however not studied enough for finding exact results by a literature search. There is a lot of information available about one feeding method. Many methods presented in this work were studied only in one set of experiments. It is difficult to compare the feeding methods to one another because the welding experiments were in most cases different from one another. The characteristics of each feeding method are however evident.

This study discusses and does provide the basic characteristics of the most common shielding methods in laser welding. A thorough study of this subject has yet to been published. The results of this literature survey can be utilized for designing gas shielding in laser welding. The use of these results is not narrowed to only low alloy steels. The results do provide information about the phenomena of gas shielding in laser welding.

Bead on plate configuration was used in several articles. This is not an ideal configuration since the same process parameters do not apply with butt joints. Shielding with bead on plate configuration was demonstrated to be successful in many studies. It is however difficult to find an industrial application for this configuration, whereas a butt joint is an actual joint. By own experimental study the specific effects of certain feeding methods could be validated. This could be studied by a thorough set of experiments which should be done for a certain material thickness at a time. While other welding parameters are optimized, shielding gas feeding methods could be studied one at a time. This should be carried out for one shielding gas at a time since it has an effect in shielding conditions. Welding speed has an important role in this, thus, it should be adjusted properly since it has an effect in the size of the shielding zone.

5.1 Conclusions

The phenomena of gas shielding in fiber laser welding of low alloy steel was studied by a literature review. Analysis of different shielding gas feeding methods has led to following conclusions:

1. The size of the shielding area depends mainly of welding speed and thickness of the material in keyhole welding.

2. On many occasions one nozzle provides sufficient shielding. An optimal nozzle inclination angle providing the longest shielding area is 15 ° with high density gases. In order to obtain deeper welds a double nozzle with an inner jet provides better penetration and shielding for the weld.

3. By enlarging nozzle diameter and increasing flow rate of the gas a better coverage is achieved. This is especially beneficial with high density gases such as argon. However for thicker materials the use of multiple nozzles is recommendable to secure the coverage and decrease the gas consumption.

4. Environmental shielding is not a good option for welding of low alloy steels because of unreasonably high manufacturing costs of the setup. It does provide the most secure shielding which, however, is not necessary.

5. A suitable gas feeding method for laser welding can be obtained by designing shielding gas feeding case-specifically. This will lead to better welding results.

REFERENCES

Ancona, A., Sibillano, T., Tricarico, L., Spina, R., Lugarà, P.M., Basile, G. & Schiavone, S. 2005. Comparison of two different nozzles for laser beam welding of AA5083 aluminium alloy. Journal of Materials Processing Technology, Volumes 164–165, Pages 971-977.

Buschenke F., Sakkiettibutra J., Zeiler M. & Vollertsen F. 2009. Distortion during laser beam welding in consideration of the gap width. Lasers in manufacturing. Proceedings of the fifth international WLT-Conference on laser in manufacturing. Munich. Germany. German scientific laser society. Pages 33-38.

Eriksson I., Powell J. & Kaplan A. F. H. 2011. Measurements of fluid flow front during laser welding. Science and technology of welding and joining. Volume. 16 Number 7. Pages. 636-641.

Geiger, M., Kägeler, K. & Schmidt, M. 2008. High-power laser welding of contaminated steel sheets. Production Engineering, September, Volume 2, Issue 3, Pages 235-240.

Grevey, D., Sallamand, P., Cicala, E. & Ignat, S. 2005. Gas protecting optimization during Nd:Yag laser welding. Optics & laser technology, Volume 37, Issue 8, Pages 647-651.

Kaplan A. F. H., Westin E. M., Wiklund G. & Norman P. 2008. Imaging in cooperation with modeling of selected defect mechanisms during fiber laser welding of stainless steel. Congress proceedings. ICALEO. 27th international congress on applications of laser & electro-optics. October 20-23. Temecula, CA, USA. Laser institute of America. Pages 789-789.

Kaplan, A. & Wiklund, G. 2009. Advanced welding analysis methods applied to heavy section welding with a 15 kW fibre laser. Welding in the World, Volume 53, Special issue, Pages 295-300.

Karkhin V. A., Homich P. N. & Michailov V. G. 2007. Analytical-experimental technique for calculating the temperature fields in laser welding. 11th Nolamp conference in laser processing of materials, Lappeenranta, August 20-27. Pages 21-27

Katayama, S., Abe, Y., Mizutani, M. & Kawahito, Y. 2011. Deep penetration welding with high power laser under vacuum. Transactions of joining and welding research institute, Volume 40, Number 1, Pages 15-19.

Katayama S., Hirayama M., Mizutani M. & Kawahito Y. 2011. Deep penetration welds and welding phenomena with combined disk lasers. Congress proceedings. ICALEO. 30th international congress on applications of laser & electro-optics. October 23-27. Orlando, FL, USA. Laser institute of America. Pages 661-668.

Katayama S., Kawahito Y. & Mizutani M. 2007. Plume behaviour and melt flows during laser and hybrid welding. Lasers in manufacturing. Proceedings of the fourth international WLT-conference on laser manufacturing, Munich, Germany June 18th-22nd. Pages 265-271.

Katayama, S., Kawahito, Y. & Mizutani, M. 2010. Elucidation of laser welding phenomena and factors affecting weld penetration and welding defects. Physics Procedia, Volume 5, Part B, Pages 9-17.

Kawahito, Y., Mizutani, M. & Katayama, S. 2007. Investigation of high power fiber laser welding phenomena of stainless steel. Transactions of joining and welding research institute, Volume 36, Number 2, Pages 11-15.

Kou, S. 2003. Welding metallurgy. 2 edition. New York: Wiley, cop. 461 p.

Kuo T. Y. & Lin Y. D. 2007. Effects of different shielding gases and power waweforms on penetration characteristics and porosity formation in laser welding of inconel 690 alloy. Materials transactions, Volume. 48, Number 2. Pages 219-226.

Lappalainen E., Purtonen T. & Salminen A. 2012. Fiber laser welding of structural steel – bead on plate versus butt joint. Proceedings of the 7th international conference. Russia. St. Petersburg, September 18-21. Saint Petersburg Publishing house SPbSPU. P. 258-265.

Liu Z., Kutsuna M. & Xu G. 2006. Fiber laser welding of 780 MPa high strength steel. Congress proceedings. ICALEO. 25th international congress on applications of laser & electro-optics. October 30- November 2. Scottsdale, AZ, USA. Laser institute of America.. P. 562-568.

Maol ry. 2006. Maol taulukot. Otavavan kirjapaino. Keuruu. 167 p.

Mei, L., Chen, G., Jin, X., Zhang, Y. & Wu, Q. 2009. Research on laser welding of high-strength galvanized automobile steel sheets. Optics and Lasers in Engineering, Volume 47, Issue 11, November, Pages 1117-1124,

Patschger, A., Sahib, C., Bergmann, J.P., & Bastick, A. 2011. Process Optimization through Adaptation of Shielding Gas Selection and Feeding during Laser Beam Welding. Physics Procedia, Volume 12, Part A, Pages 46-55.

Quintino, L., Costa, A., Miranda, R., Yapp, D., Kumar, V. & Kong, C.J. 2007. Welding with high power fiber lasers – A preliminary study. Materials & Design, Volume 28, Issue 4, Pages 1231-1237.

Quintino, L., Miranda, R.M., Williams, S. & Kong, C.J. 2011. Gas shielding in fiber laser welding of high strength pipeline steel. Science and Technology of Welding and Joining, volume. 16, no. 5, Pages 399-404.

Reed, C. B., Natesan, K., Xu, Z. & Smith, D. L. 2000. The effect of laser welding process parameters on the mechanical and microstructural properties of V-4Cr-4Ti structural materials. Journal of nuclear materials, Volumes 283-287, Pages 1206-1209.

Reisgen, U., Olschok, S. & Jakobs, S. 2013. Laser beam welding under vacuum in comparison to electron beam welding. Proceedings of the 7th international conference.

Russia. St. Petersburg, September 18-21, 2012. Saint Petersburg Publishing house SPbSPU. Pages 113-129.

Reisgen, U., Schleser, M., Mokrov, O. & Ahmed, E. 2010. Shielding gas influences on laser weldability of tailored blanks of advanced automotive steels. Applied Surface Science, Volume 257, Issue 5, 15 December, Pages 1401-1406.

Salminen, A., Lehtinen, J. & Harkko P. 2008. The effect of welding parameters on keyhole and melt pool behavior during laser welding with high power fiber laser. Congress proceedings. ICALEO. 27th international congress on applications of laser & electro-optics. October 20-23. Temecula, CA, USA. Laser institute of America. Pages 354-363.

Salminen A. & Fellman A. 2007. The effect of laser and welding parameters on keyhole and melt pool behavior during fiber laser welding. Congress proceedings. ICALEO. 26th international congress on applications of laser & electro-optics. October 29- November 1. Orlando, FL, USA. Laser institute of America. Pages 416-425.

Salminen, A., Lappalainen, E. & Purtonen, T. 2013. Basic phenomena in high power fiber laser welding of thick section materials. 37th Matador conference, CIRP, Manchester 25-27.7.2012. Springer-Verlag London. Pages 331-336.

Salminen A., Piili H. & Purtonen T. 2010. The characteristics of high power fibre laser welding. Journal of mechanical engineering science. Volume 224 Part C5. Pages 1019-1029.

Scholz J. & Fieret J. 2012. Cutting and welding process gas for CO_2 lasers and fibre lasers. Proceedings of the 7th international conference. Russia. St. Petersburg, September 18-21. Saint Petersburg Publishing house SPbSPU. P. 350-358.

Seefeld T. & O`Neill W. 2007. High brightness laser cutting and welding. Lasers in manufacturing. Proceedings of the fourth international WLT-conference on laser manufacturing, Munich, Germany June 18th-22nd. Pages 311-271-319.

Shin, M. & Nakata, K. 2010. Weld bead formation by a 10 kW class high power fiber laser on 16 mm thickness carbon steel plate. Transactions of joining and welding research institute, volume 39, No. 1, Pages. 33-38.

Shirvan, A.J., Choquet, I. & Nilsson, H. 2012. Numerical modeling of shielding gas flow and heat transfer in laser welding process. Proceedings of The 5th International Swedish Production Symposium, Linköping, Sweden, Pages 269-276.

Sibillano, T., Ancona, A., Berardi, V., Schingaro, E., Basile, G. & Lugarà, P. M. 2006. A study of the shielding gas influence on the laser beam welding of AA5083 aluminium alloys by in-process spectroscopic investigation. Optics and Lasers in Engineering, Volume 44, Issue 10, October, Pages 1039-1051.

Sibillano, T., Ancona, A., Berardi, V., Schingaro, E., Basile, G. & Lugarà, P. M. 2007. Optical detection of conduction/keyhole mode transition in laser welding. Journal of Materials Processing Technology, Volume 191, Issues 1–3, 1 August, Pages 364-367.

Sokolov, M., Salminen, A., Kuznetsov, M. & Tsibulskiy, I. 2011. Laser welding and weld hardness analysis of thick section S355 structural steel. Materials & Design, Volume 32, Issue 10, December, Pages 5127-5131.

Sokolov, M., Salminen, A., Somonov, V. & Kaplan, A.F.H. 2012. Laser welding of structural steels: Influence of the edge roughness level. Optics & Laser Technology, Volume 44, Issue 7, October, Pages 2064-2071.

Steen, W. & Mazumder, J. 2010. Laser material processing. 4 edition. London: Springer London. 558 p.

Suder, W. & Williams, S. 2010. Parameter selection in laser welding using the power factor concept. Congress proceedings. ICALEO. 29th international congress on applications of laser & electro-optics. September 26-30. Anaheim, CA, USA. Laser institute of America. Pages 654-659.

Tani, G., Ascari, A., Campana, G. & Fortunato, A. 2007. A study on shielding gas contamination in laser welding of non-ferrous alloys. Applied Surface Science, Volume 254, Issue 4, 15 December 2007, Pages 904-907.

Tsukamoto S., Zhao L., Arakane G., Sugino T. & Yasuda K. 2010. Prevention of porosity in deep partial penetration laser and hybrid welding with minimum oxygen in the weld metal. Congress proceedings. ICALEO. 29th international congress on applications of laser & electro-optics. September 26-30. 2010. Anaheim, CA, USA. Laser institute of America. Pages 618-625.

Veerhaeghe, G. & Hilton, P. 2005. Battle of the sources – using a high power Yb-fibre laser for welding steel and aluminium. Proceedings of the IIW conference on benefits of new methods and tends in welding to economy, productivity and quality, 10–15 July, Prague, Czech Republic. Pages 188–200.

Vänskä, M., Purtonen, T. & Salminen, A. 2012. Ruostumattomien teräsputkien orbitaalileikkaus ja –hitsaus kuitulaserilla. Hitsaustekniikka, 5/2012, Pages 15-19.

Wang, H., Shi, Y., Gong, S. & Duan, A. 2007. Effect of assist gas flow on the gas shielding during laser deep penetration welding. Journal of Materials Processing Technology, Volume 184, Issues 1–3, 12 April, Pages 379-385.

Yang, S., Carlson, B. & Kovacevic, R. 2011. Laser welding of high-strength galvanized steels in a gap-free lap joint configuration under different shielding conditions. Welding journal, 1/2011, Vol. 90. Pages 8-18.

Zhao, L., Tsukamoto, S., Arakane, G., Sugino, T. & DebRoy, T. 2011. Influence of oxygen on weld geometry in fibre laser and fibre laser–GMA hybrid welding. Science and Technology of Welding and Joining, Volume 16, Number 2, Pages 166-173.

Zhao L., Tsukamoto S., Arakane G. & Sugino T. 2009. Influence of oxygen on weld geometry in fibre laser welding. Congress proceedings. ICALEO. 28th international congress on applications of laser & electro-optics. November 23-27. Orlando, FL, USA. Laser institute of America. Pages 759-765.

Zhang X., Ashida E., Katayama S., Mizutani M., Anma Y. & Luo X. 2007. High power fibre laser welding of thick steel at low welding speed. Congress proceedings. ICALEO. 26th international congress on applications of laser & electro-optics. October 29-November 1th. Orlando, FL, USA. Laser institute of America. Pages 690-696.

Zhang X., Ashida E., Tarasawa S., Anma Y., Okada M., Katayama S. & Mizutami M. 2009. Welding of thick section stainless steel plates up to 50mm with high brightness lasers. Congress proceedings. ICALEO. 28th international congress on applications of laser & electro-optics. November 2-5. Orlando, FL, USA. Laser institute of America. Pages 690-696.