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VTT Industrial Systems

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Abstract

Autogenous laser welding has shown many advantages over traditional welding methods in numerous applications. Still the process has disadvantages, which are impeding the applicability for the wider industrial use, e.g. tight tolerances in groove manufacturing, fixturing of the pieces against distortions and limited area of thicknesses. Owing to these limiting factors, a great deal of research work has been carried out to overcome these disadvantages by different ways.

In many studies it has been pointed out that by using filler metal with laser welding, it is possible to reduce the above-mentioned limitations. The gap bridging ability is then increased strongly and the filler wire plays an important role also when welding thicker sections by using a narrow gap joint configuration and multi pass technique. Recently so-called hybrid welding, which is a combination of the laser beam and arc welding process, has been a target of great interest. A hybrid process seems to be very effective in overcoming the reductions of autogenous laser welding. Not only for the reason of filler wire addition, but also for the extra heat coming from the arc to make the process more effective by increasing the welding speed.

In this study filler wire and an arc were used with an Nd:YAG laser in the way of a multi pass technique to weld thick austenitic stainless steel sections. To reduce the welding time and distortions, very narrow grooves were used. The applicability of the laser welding with filler wire was shown, up to a thickness of 20 mm using a 3 kW Nd:YAG laser. Hybrid welding was introduced to the narrow groove by the help of stabilizing, guiding and the contraction effect of the laser beam to the arc discharged. The applicability was shown for a groove angle of 10^{o} and thickness of up to 30 mm.

Preface

The studies for this thesis have been carried out in the Technical Research Centre of Finland (VTT) in Lappeenranta and belong to the tasks in which manufacturing of the vacuum vessel of International Thermonuclear Experimental Reactor (ITER) were researched. The tasks were financed by The National Technology Agency (Tekes), European Fusion Development Agreement (EFDA) and VTT.

I am indebted to Professor Veli Kujanpää for supervising my work with valuable guidance and discussions. I would also like to thank my colleagues in the Laser team in VTT Industrial System, especially Vesa Airas, Miikka Karhu and Mikko Pesari for their assistance in the experimental work, and Henrikki Pantsar and Antti Salminen from LUT for fruitful discussions. My former colleague Ismo Meuronen is acknowledged for the excellent guidance to the working life.

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I am also thankful to my friends and family for their support. Especially I would like to give my thanks to my parents, Väinö and Tuula, to the family of my brother, Teijo, Päivi, Arttu and Antti and to my sister, Tanja and her boyfriend Tommi. Also I am grateful to Ensio, Kaija, Jukka and Riikka.

Special thanks go to my closest family; Niina, Anni-Kaisa and Vilppu. You have been extremely patient and understanding about my work and absence from home. Also the joy and support, which you gave me during the work, was inexpressibly valuable.

Contents

Abbreviations and symbols

AlMg3		Aluminium alloy with magnesium
Ar		Argon
CCD		Charge Coupled Device
CO_2		Carbon dioxide
CW		Continuous wave
DC		Direct Current
He		Helium
MAG		Manual Active Gas
MIG		Manual Inert gas
Nd:YAG		Neodium, Yttrium Aluminium garnet
NGTIG		Narrow gap Tungsten Inert Gas
TIG		Tungsten Inert Gas
TWIN spot		Optical arrangement, in which two laser spots have an effect on the same process
A_G	mm^2	Groove cross-sectional area
A_W	mm^2	Filler wire cross-sectional area
a_t		Attenuation of the laser power
b	mm	Stickout of the filler wire
D	mm	Diameter of the laser beam at the collimator
d	mm	Diameter of the focal point

D_{LA}	mm	Distance between the arc impingement point and a point of the laser beam at the surface of the workpiece
D_t		Torch orientation in hybrid welding
D_W		Filler wire feed direction
d_W	mm	Diameter of the filler wire
F	mm	Focal length
f	mm	Focal point position
F_Y	mm	Filler wire position transverse to the welding direction and the laser beam optical axis
F_Z	mm	Filler wire position in the direction of the laser beam optical axis
h_{Fill}	mm	The filling effect of the pass in the groove
h_1	mm	Distance from the surface of the testpiece to the surface of the root pass in the groove
h_2	mm	Distance from the surface of the testpiece to the surface of the first filling pass in the groove
I	A	Current
L_m	J/kg	Latent heat of melting
P_E	mm^2/mm	Penetration effectiveness
P_L	kW	Laser power
R		Reflectivity
s	mm	Plate thickness

T_o	K	Room temperature
T_m	K	Melting temperature
U	V	Voltage
V	mm^3/s	Volume in time
V_L	mm^3	Groove volume
W_R	m/min	Filler wire feed rate
V_W	m/min	Welding speed
V_{WMAX}	m/min	Maximum welding speed
W_X	mm	Filler wire position in the welding direction according to the focal point of the laser beam
W_Y	mm	Filler wire position in a horizontal direction according to the focal point of the laser beam
W_Z	mm	Filler wire position in a vertical direction according to the focal point of the laser beam
α_t	^{o}	Torch angle
α_W	^{o}	Angle of the filler wire
β	^{o}	Groove angle
θ	^{o}	Focusing angle
ρ	kg/mm^3	Material density

1. Introduction

1.1 General

Laser welding has shown many advantages over traditional welding methods in numerous applications. The advantages are mainly based on the very precise and powerful heat source of laser light, which changes the phenomena of the welding process when comparing to conventional processes. With the help of an intense power source, the so-called keyhole welding mechanism can be utilized. In this mechanism a laser beam forms a narrow vapour channel called "keyhole" through the whole thickness to be welded or penetrates the metal a certain distance according to the power of the laser used. According to the phenomena of keyhole welding, penetration is deeper and the welding speed higher than with conduction limited welding. Owing to the precise power source and high welding speed, the heat input to the workpiece is small and distortions are minimal. Also the shape of the laser weld is less critical for distortions, especially angular ones, than traditional welds.

Usually laser welding is used in an autogenous way, e.g. without filler metal. As it has been pointed out, due to that way laser welding shows it's most effective sides. According to the present power level of lasers used in the welding of metals, typically the thickness of welded plates is below 20 mm. However, there is a need for thicker section welding with reduced distortions for example in the case of large plate constructions. In addition, autogenous laser welding demands tight tolerances in groove manufacturing and fixturing of pieces to be welded. Owing to these needs and limitations, a great deal of research work has been carried out to overcome these disadvantages of ordinary laser welding.

In many studies it has been pointed out that by using filler metal with laser welding, it is possible to reduce these limitations. Quite a flexible method to introduce the filler metal to the joint, is the dynamic feeding of filler wire during the process. Gap bridging ability is then increased strongly. The filler wire plays an important role also when welding thicker sections than can be welded by a single pass technique. Together with a narrow gap joint configuration and multi pass technique it has been shown to be possible to weld thicker sections of good quality and lower total heat input, which leads to smaller distortions.

Recently so-called hybrid welding, which is a combination of the laser beam and arc welding process, has been a target of great interest not only in the research field but also for industrial use. A hybrid process seems to be very effective in overcoming the reductions of autogenous laser welding. Not only for the reason of filler wire addition, but also for the extra heat coming from the arc to make the process more effective by increasing the welding speed. Although hybrid welding has been introduced over two decades ago, (Eboo et al., 1978, Steen, 1980) it has not yet been utilized for multi pass welding of thicker sections with a narrow groove. Based on the studies, which show the guiding and contraction effect of the laser beam to the arc discharged, applicability of hybrid welding with a narrow groove is obvious.

1.2 Problem statement and work definition

In this study filler wire and an arc were used with an Nd:YAG laser in a multi pass technique to weld thicker austenitic stainless steel sections. To reduce the welding time and distortions, very narrow grooves were used with filler metal and a multi pass technique. Experiments were made according to the limitations made by the final application, in which processes developed could be used. These limitations came mainly from welding of a thick section on one side only. Then groove enlarges towards the upperside of the joints to be welded and cause angular distortions. By reducing the opening of the groove and using a keyhole mechanism, which allows the heat input to concentrate evenly through the whole penetration, the distortions can be kept at a moderate level.

In order for the laser welds to reach a certain quality, the stability of the keyhole is crucial. It should be open all of the welding time. Instability of the keyhole may produce incomplete penetration, bubbles and craters when the molten metal of the keyhole walls collapse. Owing to the narrow gap and use of filler wire and arc, circumstances for a stable keyhole are difficult especially at the bottom of the groove. Also because of incomplete penetration the keyhole is unstable.

Hybrid welding has been recently used for laser welding applications. The main point of the experiments and applications reported has been in the usability of the groove manufacturing method by which tolerances are not so limited or stringent. Also extra heat coming from the arc discharging has been used to increase the welding speed and thus the effectiveness of production. In this study hybrid welding has been used in a novel way through a narrow groove by the help of Nd:YAG laser.

The materials used in the welding experiments of this thesis were two different kinds of austenitic stainless steel. However, the procedure described can be utilized for carbon steels also. The main differences that will arise with other materials are based on the different heat conductivity, the microstructure changes and the coefficient of heat expansion. According to the problem statement, no great attention has been put on the metallurgical aspects of the weld and heat affected zone.

1.3 Overview of the thesis

This thesis introduces novel way to use a medium power Nd:YAG laser together with filler wire feeding and arc welding in order to maximize the effectiveness of a welding in thick section. In Chapter 2 the theoretical background of filler wire welding with a laser is presented especially from the point of view of multi pass welding. Also in Chapter 2, the mechanism and main point of hybrid welding is introduced more precisely.

In Chapter 3 experimental procedures of the experiments, in which laser welding with filler wire and hybrid welding utilized by a multi pass technique in a narrow groove, are presented. Also experiments with single pass welding are described in order to illustrate the processes. Chapter 4 presents the results of the experiments and in Chapter 5 a discussion according to those and former work reported is made. Industrial applicability as well as future vision of the processes is included in Chapter 6.

1.4 Contribution of the thesis

When welding thick sections with lasers, the machines used have been CO_2 lasers with very high power. Due to that, grooves have been quite wide and the number of passes limited. Within procedure with an Nd:YAG laser and multi pass technique introduced in this thesis, quite moderate power level lasers can be used in welding very thick sections. Also the opening of the grooves is much smaller than used before. This kind of procedure is possible according to the nature of the Nd:YAG laser light. Use of a medium power Nd:YAG laser with the procedure introduced in this thesis, means the equipment cost of laser can be reduced because of the usability of the lower power laser in the welding of thick sections. Welding still occurs with the keyhole mechanism, which minimizes the metal to be melted and therefore distortions.

In this work, it has been established that with the help of filler wire feeding and arc welding, it is possible to increase the thickness of the plates to be welded by a medium power Nd:YAG laser. It has also been introduced that hybrid welding is possible in very narrow grooves, although according to the nature of the arc, accurate discharging in a narrow groove is not possible by arc welding itself. This process combination has not been utilized before, although a hybrid process nowadays is one of the used processes among others with single pass welding.

2. Theoretical background

2.1 Laser welding with filler wire

During the last decades, laser welding has shown incontrovertibly its effectiveness and advantages over traditional welding methods in many studies and also in industrial applications. As a result of process-specific properties of welding with a laser beam, such as the high concentration of energy with a small effective cross-section, low total thermal input, small seam cross-sections (volume of molten pools), high depth-to-width ratios (deep welding effect) and high welding speeds, a large number of innovative developments have been introduced. The advantages referred to above are coming from the powerful, precise and highly concentrated heat source of a laser beam. The interaction of a laser beam with a material is dominated by deep welding effect. This brings about the possibility to use so-called "keyhole" welding phenomenon, in which the laser beam penetrates in to a certain depth of the material. Normally the penetration of the laser beam and according to that, weld penetration, is used for single pass welding through the whole thickness. Thus penetration is tied down to the power of the laser used. Although thickness of up to 50 mm can be welded with exceptionally high power lasers, the common thickness range is up to 20 mm, which means a laser power of up to 20 kW. (Steen, 1991, Dawes, 1992, Dahmen et al., 1999)

According to the phenomenon of autogenous laser welding, tight geometrical joint tolerances of the joint has to be fulfilled in accomplishing satisfactory weld quality. This requires that the grooves are very precisely manufactured, the laser beam and parts to be welded must be accurately positioned and secured during welding. If unwanted factors e.g. offset edges, imprecise edge preparation, a joint gap or offset beam, occurs, unacceptable seam qualities will be produced. In autogenous laser welding, the weld metal properties achieved are the results of two factors; composition of the parent material and heat cycle of the process. Thus influence on the mechanical properties of the weld is limited. (Panten et al., 1990, Schinzel et al., 1998)

It has been widely reported that by using filler metal with laser welding, the above-mentioned restrictions can be overcome. The filler metal reported has been in the form of powder (Shannon and Steen, 1996) or filler wire, which is dynamically fed to the process. The use of filler wire in laser welding allows joint fitup tolerances to be relaxed to a level suitable for industrial implementation. It also provides a means of controlling the metallurgy of the weld bead and ensures weld quality. These improvements introduced by filler metal are accompanied with a loss of some of the advantages of autogenous laser welding. The primary concern is the welding speed, and thus energy input. In addition, the number of parameters increases significantly, and the nature of the process changes somewhat, and so the welding procedure itself is more complex than that for an autogenous weld. On the other hand in laser welding with a filler wire procedure, wire is fed directly into the gap and so molten filler metal fills the gap with minimal melting of the base material. Thus when this technique is combined with a multi pass welding technique, there is no limitation in weldable thickness, in principle. (Arata et al., 1986, Panten et al., 1990, Coste et al., 2001a, Ion et al., 2001)

The differences between CO_2 and a Nd:YAG laser in welding with filler wire, is coming from the wavelength. Due to the one order shorter wavelength of the Nd:YAG laser (1.06 μm), it has considerably better absorption to both the filler wire and also to the parent material. Better absorption is also the reason, why the Nd:YAG laser with filler wire has been mainly studied and used in the welding of aluminium alloys. Another reason is that aluminium alloys used in the automobile and transportation industry, are sensitive alloys for hot-cracking. By using filler wire the crack sensitivity can be restricted significantly. Another advantage of the shorter wavelength of Nd:YAG laser is, that it is less sensitive to plasma produced by vapourization of material. This allows deeper penetration and the process does not need carefully made gas injection as for welding with a CO_2 laser. (Schinzel et al, 1998, Salminen, 2001a, Ion et al., 2001)

Traditionally thick plates have been welded using high power CO_2 lasers. The power level of Nd:YAG lasers nowadays cannot reach the level of CO_2 lasers. However, quite recently it has been shown, and reported, that the use of a Nd:YAG laser to weld thick steel sections of up to 60 mm by using a narrow groove, filler wire feeding and multi pass welding technique is possible. (Ishide et al., 1997, Coste et al., 2001a)

2.1.1 Principle and the parameters of the process

In *Fig. 2.1* the principle of laser welding with filler wire is shown. Normally the laser beam is perpendicular to the workpiece and the filler wire is fed to the process at a certain angle. According to the welding direction, the filler wire can be fed to the process from the leading edge or trailing edge. Depending on the feed direction, the interaction point between the laser beam and filler wire differs.

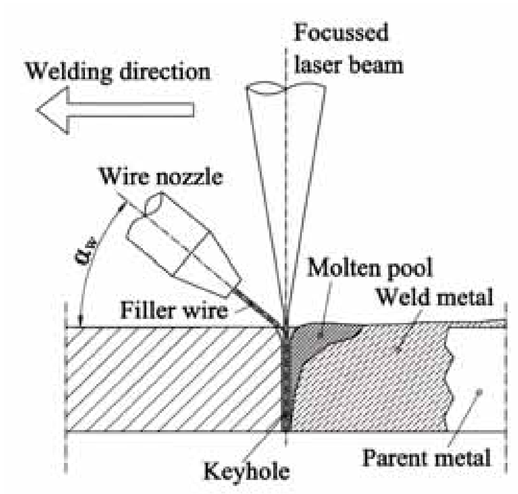


Figure 2.1. Schematic picture of the principle of the laser welding with filler wire.

When the laser beam hits the surface of the material, absorption takes place and the material starts to melt and vapourize. Absorption of the laser beam increases with increasing temperature. With a laser beam intensity of 10^6 W/cm^2 or higher, iron alloys start to vapourize. Pressure of the vapourized metal forms a crater into the material. This crater deepens according to the pressure of metal vapour, and if the laser beam intensity is high enough, a vapour cavity called a "keyhole" is formed. A keyhole with molten edges is maintained by the equilibrium of forces caused by the laser beam, metal vapour, material surface tension and gravity. As the beam penetrates into the material, energy is absorbed through the entire penetrated depth and the keyhole reaches as deep into the material as possible depending on the energy input. When the beam is moved along the joint and as the keyhole proceeds, the material melts from the front of the keyhole, flowing around the keyhole to its trailing edge where it solidifies and forms a weld. Equilibrium state of the keyhole should be achieved when moving laser beam along the joint in order to produce quality welds. (Sasaki et al., 1986, Steen, 1991, Salminen, 2001b)

The main aim for a successful process, when the filler wire is introduced is that it does not disturb the equilibrium state of the keyhole and the flow of liquid metal. For reliable melting of the wire it has to be adjusted with increasing accuracy with respect to increasing feed rate and decreasing focal diameter. An optimum adjustment is characterized by the formation of a stable "bridge" of melt in which additional material passes into the melt. In the case of maladjustment, weld defects such as voids and insufficient root formation will occur as well as the process becoming unstable. (Sasaki et al., 1986, Dawes, 1992, Dahmen et al., 1999)

For laser beam welding with filler wire further wire-specific parameters must be added to the usual process parameters (*Fig. 2.1*):

* Interaction point between the laser and filler wire
* Welding direction (or wire feed direction)
* Wire feed angle
* Wire feed rate.

Interaction point

The position, in which the filler wire meets the laser beam and/or the weld pool, is the most important setting for the smooth transfer of filler material into the process. The best welding results have been achieved with a CO_2 laser if the wire tip is positioned at the point of impingement of the laser beam at the surface of the material, *Fig. 2.2*. According to the laser power used e.g. the size of the molten pool the deviations from this point can be about 1 mm. The most stringent tolerance is for accuracy of W_Z, because in the case of even a slight shift of the wire (0.3 mm) from this position the filler wire could project into the beam path and cause excessive spatter, vapourize and form a plasma cloud which re-radiates beam energy elsewhere. Another possibility is that the wire moves back from or to the side of the keyhole, causing the wire to either stick to the work surface, or alternatively, causes the unheated wire to snake off in another direction. *Table 2.1* reviews the positions leading to good quality welds according to the literature. (Panten et al., 1990, Dawes, 1992, Salminen, 2001b)

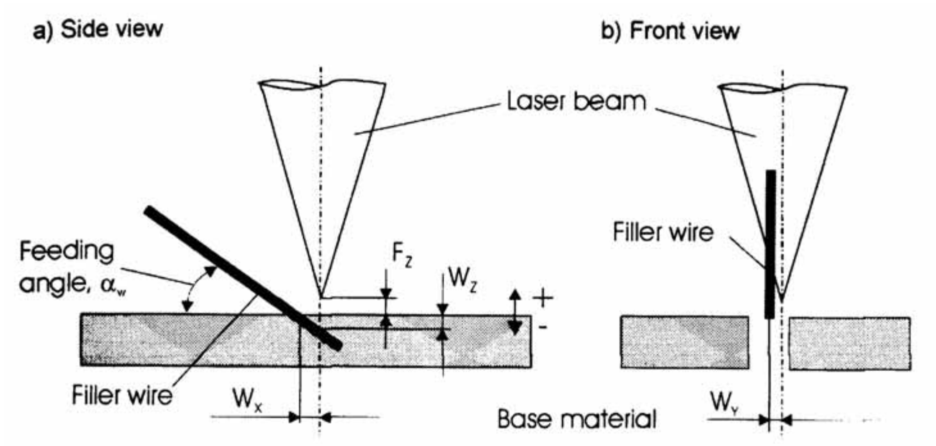


Figure 2.2. The positioning of the filler wire relative to the laser beam, workpiece surface and joint during laser welding. W_Y is the distance between the wire and the laser beam in an optical axis, W_Z is the vertical distance of the wire - beam interaction point from the workpiece surface. W_X is the distance from the wire surface at the workpiece surface level and α_W is the feed angle between the work piece surface and the wire. (Salminen, 2001b)

Table 2.1. Wire feeding and focal point positions used in CO_2 laser welding with filler wire (Salminen, 2001b).

Focal point position		Wire feed position			Feed angle	Feed direction
F_Z [mm]	F_Y [mm]	W_X [mm]	W_Y [mm]	W_Z [mm]	α_W [^{O}]	
0–6	0	0–6	0–0.3	0–6	35–70	Leading
0	0	0–2	0	0–1	35–40	Trailing

Also in Nd:YAG laser welding with filler wire, the wire is normally fed directly into, or slightly ahead of the beam at the workpiece, when using leading edge configuration of filler wire feeding, *Fig. 2.3*. Of the two misalignments shown (long and short), the long alignment is more detrimental to the welding process. In the long position the wire occludes the beam and prevents it from coupling adequately with the workpiece, often resulting in poor welds. (Jokinen et al., 1999, Meinert et al., 2000)

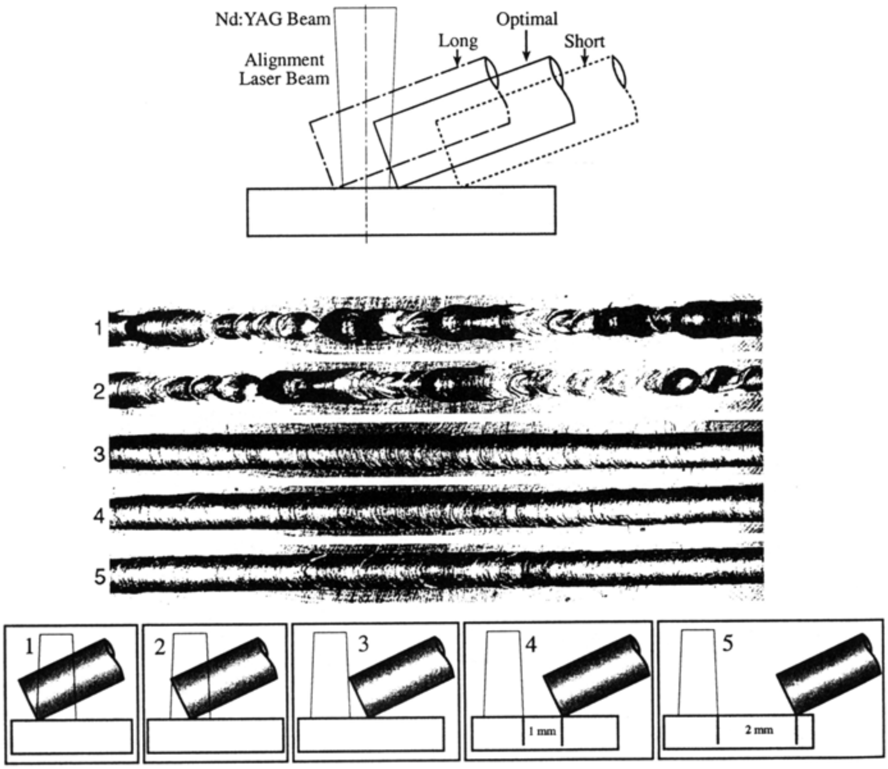


Figure 2.3. Different wire feeding placements in an Nd:YAG laser with filler wire and photographs of the weld bead. 2 kW, wire diameter 1.125 mm. (Meinert et al., 2000)

Side to side alignment of the wire with the laser beam is optimal, when the wire is aligned directly with the beam, *Fig. 2.4*. However, in the case of Nd:YAG and it´s short wavelength, quality welds can be reached up to the point where the outside of the wire touches the edge of the aligned laser beam. Poor weld has been attained with a filler wire diameter of 1.125mm, when the gap between the wire and the alignment laser beam has increased to 0.25 mm. (Meinert et al., 2000)

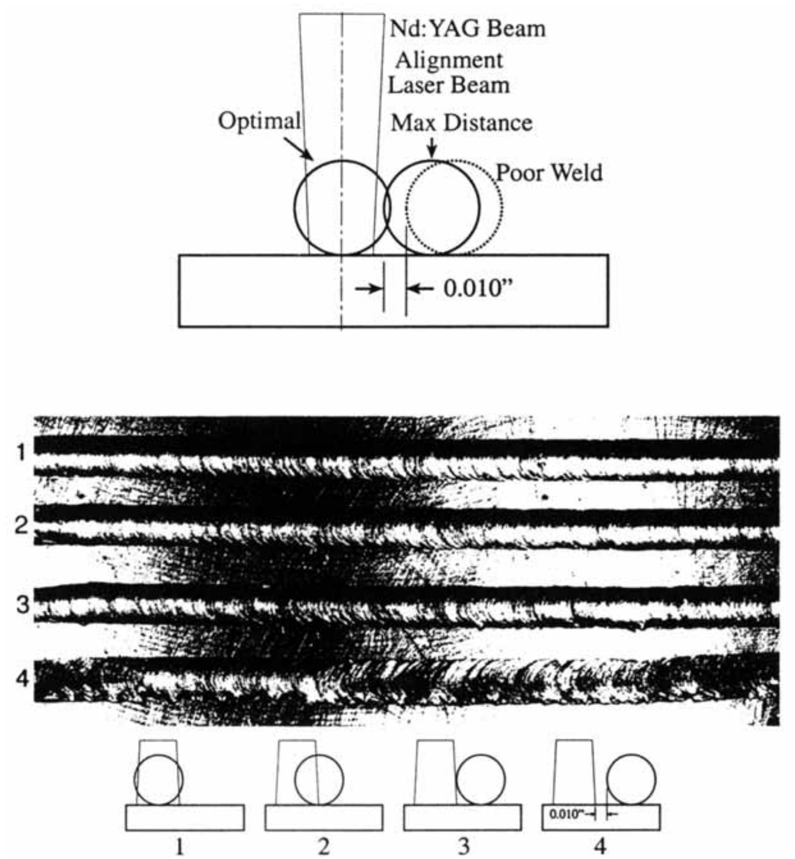


Figure 2.4. Different wire feeding side to side placements in an Nd:YAG laser with filler wire and photographs of weld beads. 2 kW, wire diameter 1.125 mm. In Fig 0.010" = 0.025 mm (Meinert et al., 2000)

Torch orientation

In laser welding with filler wire, both the leading edge and trailing edge feed direction can be used. Where a smooth and stable process is concerned, leading edge feeding has proved to be a better direction. In the case of trailing edge feeding, there is a risk of the wire tip coming in contact with the top bead of the weld building up, behind the keyhole, and sticking to it. (Panten et al., 1990, Dahmen et al., 1999, Meinert et al., 2000)

Wire feed angle

The angle at which the wire is fed relative to the workpiece normally lies between 10–60°, and angles in the range of 30–45° have proved to be most suitable. When fed into the weld pool the angle has little effect, but when fed into the beam the angle plays a major role in determining the energy absorbed by the weld. Recent studies have shown a marked increase in the absorptivity of a Nd:YAG laser beam by the filler wire, in comparison with a CO_2 laser beam, which results in a process efficiency. (Panten et al., 1990, Ion et al., 2001, Salminen, 2001a)

Restrictions on the feed angle are coming from two causes. Angles greater than 60° make the accuracy of positioning the wire in the process difficult. Where angles less than 30° cause the wire to intersect with a large area of the laser beam, causing melting and vapourization of the wire without incorporating it in the weld pool. (Dawes, 1992, Meinert et al., 2000)

Wire feed rate

The wire feed rate for a given gap and plate thickness is an important parameter and is dependent on welding speed, the cross-sectional area of the gap and the cross-sectional area of the filler wire. The relationship is expressed in *Equation 2.1*.

$$W_R = \frac{V_W \cdot A_G}{A_W} \qquad (2.1)$$

in which

W_R = wire feed rate [m/min], A_G = cross-sectional area of a groove geometry [mm^2], V_W = welding speed [m/min], A_W = cross-sectional area of the filler wire [mm^2]

In order to increase the effectiveness of the process e.g. the amount of wire to be melted, studies have been made with resistance preheating wire. Increase in the effectiveness of the process is based on two different phenomena. The heat of molten pool or absorbed laser beam more easily melts the preheated wire.

Another effect of preheating is that absorption of the laser beam is improved in comparison with using a cold wire. (Atsuta et al., 1988, Jones, 1993)

2.1.2 Gap bridging ability

One of the main features using filler wire with laser welding is the ability of gap bridging. *Fig. 2.5* illustrates the result of a literature review, in which the gap bridging ability of CO_2 laser welding with filler wire is shown. (Salminen, 2001b)

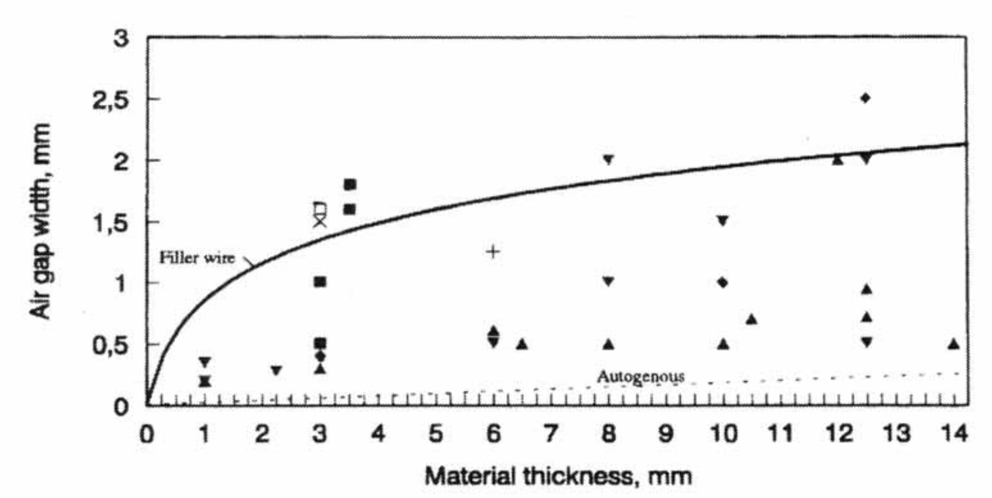


Figure 2.5. Results of a literature survey into the possibility of bridging air gaps of different widths when welding various material thicknesses. X, laser power of 1.9 kW; ●, laser power of 3.0 kW; +, laser power of 5.0 kW; ♦, 2 kW< laser power< 5 kW; ▼ laser power > 10 kW. Filler wire line is estimation for maximum practical air gap. Autogenous line is based on literature (Salminen, 2001b)

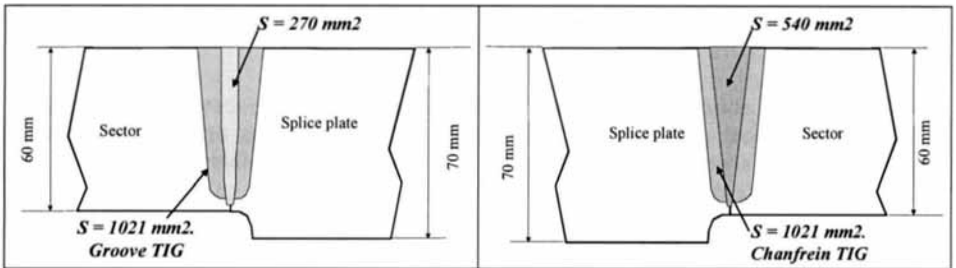
With laser welding using filler wire, the laser beam is focused on the surface of the supplied wire, and melted metal forms at the wire tip. The shape of the parting of this melted metal from the wire changes according to the wire feed speed under a constant beam power output. When the wire supply speed is low, large drops part from the wire tip, while parting occurs in the form of splashing at high speed. If the wire tip is in the groove, melt drops will adhere to the groove surfaces. By transfer of heat from the melt drops, fusion of the groove surface and bead forming are performed. That is why a joint gap which is slightly wider than the diameter of the filler wire is recommended in practice whenever possible. (Sasaki et al., 1986, Dawes, 1992)

2.1.3 Applicability for very thick sections and a narrow groove

State of the art of welding with a CO_2 laser by a single pass technique is to weld steel material up to a wall thickness of 40 mm utilizing beam powers up of to 50 kW. (Nakajima et al., 2002) In the case of an Nd:YAG laser the same "record" is 25 mm with gas turbine materials using a beam power of 10 kW. (Ishide et al., 2002)

For thick sections, welding using a multi pass technique with filler wire and a groove has also been introduced. (Atsuta et al., 1988, Panten et al., 1990, Dahmen et al., 1999) Traditionally the procedure has been based on a high power CO_2 laser. By using a high power laser, the root pass is maximized to be equal to the maximum penetration of the laser and the rest of the groove is welded with filler wire using some kind of groove. For example a 22 kW CO_2 laser has been used in a way in which the 25 mm root pass has been welded and after that one filling pass is carried out to fill the groove of 1.5 mm wide and 10 mm deep. (Roman et al., 1994) Although multi pass welding with an Nd:YAG laser for thicker sections was revealed in 1997 (Ishide et al., 1997), the process has been used more widely quite recently. This is naturally resulting from the development of a higher power Nd:YAG laser.

In order to weld thick section steel effectively with an Nd:YAG laser, a narrow groove as possible is to be used. This minimizes the number of passes and total welding time. Narrowing the groove means longer focal distance in order to reach the bottom of it. *Fig. 2.6* shows the reduction of the groove when a longer and shorter focal length is used. However, when the focal length is longer, also the diameter of the focal point is larger. This leads to the situation in which the laser acts like a TIG heat source and real keyhole welding is not possible. *Fig. 2.6* also shows the groove of TIG welding for the same thickness. The large difference between the volumes of the grooves is evident. (Coste et al., 2001b)



Comparison Long focal length laser groove/TIG Groove. Laser: Top aperture: 6 mm, Surface 270 mm²	Comparison Short focal length laser groove/TIG Groove. Laser: Top aperture: 6 mm, Surface 540 mm²

Figure 2.6. Comparison of the grooves used in the Nd:YAG laser experiments with filler wire and conventional method TIG. On the right hand a focal length of 500 mm is used and on the left hand the length is 200 mm. (Coste et al., 2001b)

A high power Nd:YAG laser was applied to the narrow groove to weld the last 40 mm of a total thickness of 60 mm, *Fig. 2.7*. Two 4 kW Nd: YAG lasers were used with so-called TWIN spot arrangement. In that procedure two laser beams were combined through the same focusing lens, but the incoming beams were separate. This allowed two separate focal points to be guided to the groove together with the filler wire. The best results were obtained when the focal point diameters were 2.0 mm. Using this procedure, the heat source of the laser was used mainly in the same way as in a TIG process, but with a much better efficiency, higher level of deposition of filler material and higher welding speed. Also in a laser process no wearing parts are used. (Coste et al., 2001a) *Fig. 2.8* shows the groove geometry that was used and the cross-section of the welds, when the above-referred TWIN spot arrangement was used for welding in the bottom of the narrow groove.

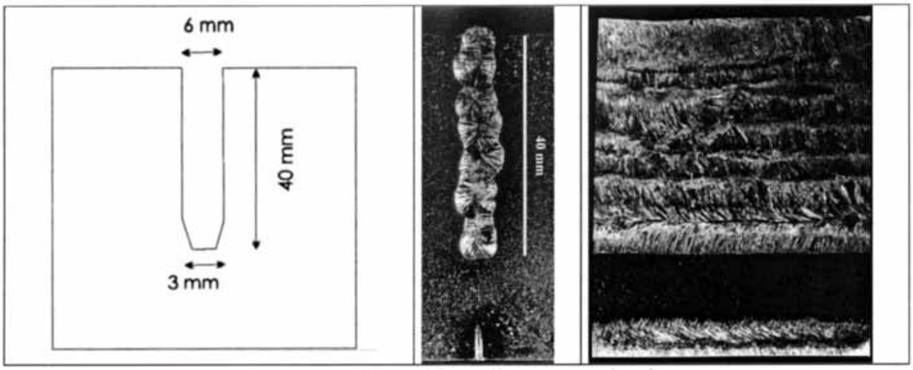


Figure 2.7. Groove geometry used and cross- and longitudinal-section of the welds of 40 mm thickness for a total plate thickness of 60 mm. Laser power 4+3 kW, TWIN spot arrangement with a 2 mm diameter focal points, focal lengths 200 mm, 6 passes. (Coste et al., 2001a)

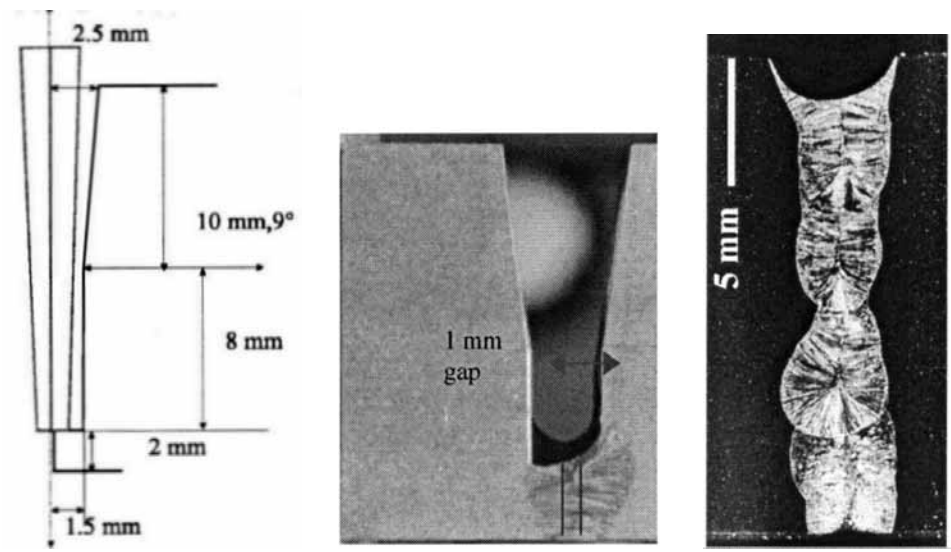


Figure 2.8. Groove geometry used, cross-section of the root weld and filling passes for a welding thickness of 20 mm. Laser power 4+3 kW, TWIN spot arrangement for a 2 mm diameter focal points, focal lengths 500 mm, 4 passes. (Coste et al., 2001b)

The above-referred results were preliminary studies for welding 60 mm thick austenitic stainless steel. *Fig. 2.9* shows the transverse and longitudinal sections of the weld in which the arrangement of two or three Nd:YAG lasers were pointed via optical fiber to two or three spots respectively. Two 4 kW lasers were used for welding a root pass and three lasers were used in the welding of the filling passes: The maximum power of the lasers together in the experiments was 11 kW. A good seam quality without pores was achieved. The total number of the passes was 15. By this configuration in which several focal points were introduced to the process the feeding of filler wire was more flexible. The drawback was that the energy density was lower than needed for deep-penetration keyhole welding. Thus the welding happened more in a conduction melting form. Even so by the welding procedure described, the productivity was shown to be 3 to 4 times higher than traditional narrow gap TIG and the total heat input was 50% smaller than with NGTIG. (Coste et al., 2002)

Figure 2.9. Transverse and longitudinal weld seam sections. 15 passes have been used to weld this 60 mm thick 316 L steel. Used configuration: TWIN spot (8kW) for the root pass and triple spot (11 kW) for the filling passes. Spot diameters 1.5 mm, welding speed 0.6 m/min, Shielding gas, nitrogen. (Coste et al., 2002)

2.2 Hybrid welding

Hybrid welding means the coupling of the energy of two different energy sources into a common process zone. This means that the laser beam and arc interact at the same time, in the same region (plasma and weld pool) and mutually influence and assist each other. Various studies have revealed that synergistic effects are achieved through coupling of the processes and the disadvantages of the individual processes can be compensated. Not only increasing penetration and welding speed are the reasons for experimenting and introducing the technology of a hybrid process to the applications, but the main advantages are coming from the gap bridging ability of the process to control the air gap coming from the groove manufacturing and fixturing tolerances. Also movement of the workpieces to be welded due to the distortions during welding can cause problems for plain laser welding by increasing the air gap. In large structures, in which distortions caused by traditional arc welding occur, quite a lot of postweld procedures such as levelling, have to be carried out. By hybrid welding, distortions can be reduced due to significantly lower heat input compared with traditional arc welding, *Fig. 2.10*. Also the mechanism of the heat input is more like laser welding than arc welding. This means that the hybrid process is more a keyhole process than a conduction process. Thus distortions of the workpiece occur more in the plane of the workpiece than bending. According to the advantages mentioned hybrid welding opens technically and commercially interesting possibilities for a multitude of applications, especially in the workshops, in which large plates and structures are handled. This opportunity has already been utilized successfully for example by one shipyard and one car manufacturer. (Eboo et al., 1978, Steen, 1980, Ishide et al., 1997, Dilthey and Wieschemann, 2000, Jokinen et al., 2000, Hyatt et al., 2001, Haferkamp et al., 2002, Jernström et al., 2002, Jokinen et al., 2002, Ono et al., 2002, Roland et al., 2002, Graf and Staufer, 2002,).

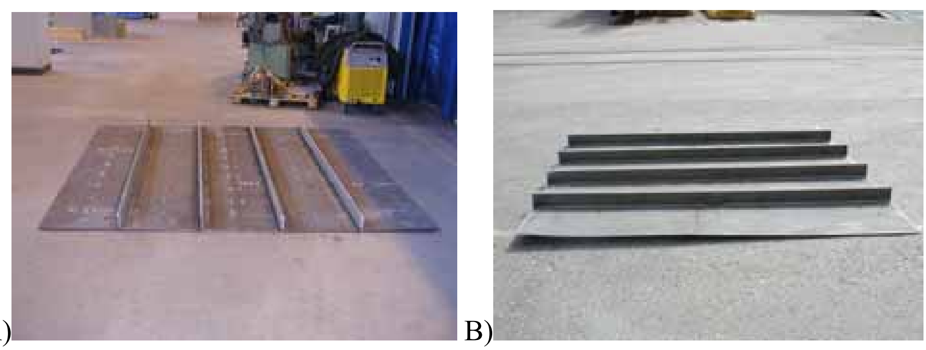
A)  B)

Figure 2.10. Shipstructure welded by hybrid welding a), and by arc welding b) (Jernström et al., 2002).

2.2.1 Principle of the process

Fig. 2.11 shows the principle of the hybrid welding process. As can be seen, normally the laser beam (CO_2 or Nd:YAG) is coming at normal incidence to the welding point, thus having the best absorptivity to the material and the highest power density. Arc of MIG/MAG, TIG or plasma welding is introduced to the process at a certain angle due to the geometrical reductions of the focusing optic of the laser used. Also special optical devices, in which both energy sources are in the vertical position, have been manufactured. This kind of arrangement is used for example with plasma welding and then the welding direction is not a process parameter as it is for the arrangement shown in *Fig. 2.11*. (Ishide et al., 1997, Fuerschbach, 1999, Dilthey and Wieschemann, 2000)

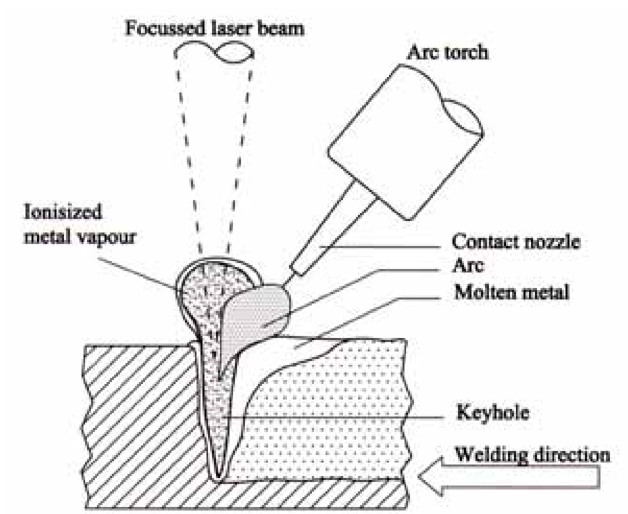


Figure 2.11. The principle of the hybrid welding process (Karhu, 2003).

As mentioned in section 2.1.1, the laser beam forms a keyhole into the material through the absorption of the laser light. When a laser beam or workpiece is moved, the liquid metal from the leading edge is flowing around the keyhole to its trailing edge, where it solidifies and forms a weld. In arc welding, the arc is maintained by thermionic emission from the sheet, *Fig. 2.12*. Charged particles between the electric poles move towards the anode or cathode according to their electric charge. These particles dissociate other molecules and the conditions for a stable arc are achieved. When the arc moves along the joint, it heats the material and thermionic emission takes place. (Lukkari, 1997)

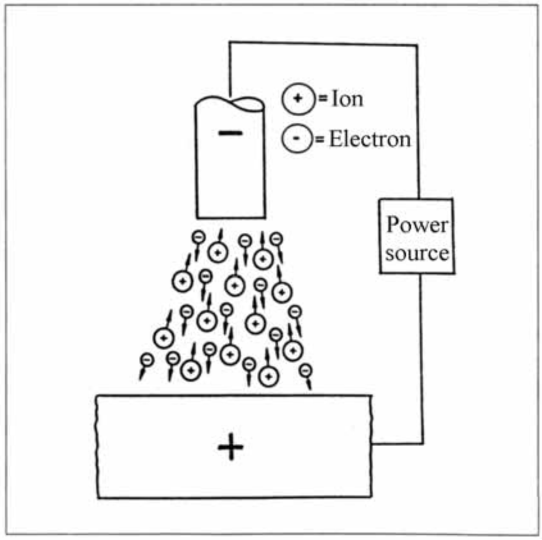


Figure 2.12. The principle of arc dissociation (Lukkari, 1997).

Successful hybrid welding demands the stable behaviour of both processes: enough laser energy should be brought to the keyhole in order to keep it in a stable condition i.e. open enough during the process, while the arc should maintain stable discharging and transferring of molten filler metal. In arc welding alone the arc is prone to instability and the weld bead width fluctuates at welding speeds similar to those used for hybrid welding, caused by insufficient heating of the material. However, during hybrid welding, the electron density in the keyhole formed by laser radiation reaches 10^{17}–10^{20} / cm^3 and surrounding area is in a molten state, so thermionic emission takes place very easily. (Ono et al., 2002) Thus, when arc welding is combined with laser welding within this region, a stable arc is maintained even at high welding speeds, *Fig. 2.13*. (Eboo et al., 1978, Steen, 1980, Makino et al., 2002)

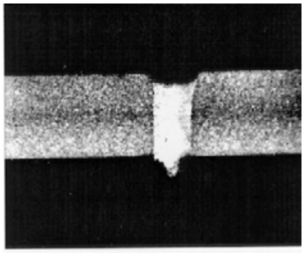
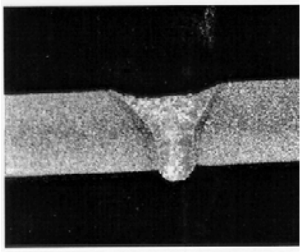
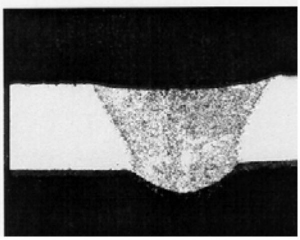
	Nd:YAG laser P_L= 1.9 kW, v_W = 5.0m/min
	Nd:YAG/MIG (DCEN) V_W = 8m/min
	MIG I=259A ; v_W = 2.0 m/min ϕ = 3.2 mm ; 45° forward Gas Ar 20 l/min Al/Mg3; s=2mm; cut edges

Figure 2.13. Welding of aluminium by means of different processes (Beyer et al., 1996).

The stabilizing effect of the laser beam can also be seen in behaviour of plasmas produced by each process during hybrid welding. *Fig. 2.14* shows the arc condition in the welding done by intentionally displacing the position of the TIG electrode to 3 mm from the beam condensing point. First, the laser was irradiated, and then the arc and keyhole were present separately at the moment of starting the arc, left in *Fig. 2.14*. Immediately thereafter, however, the arc moved in the direction of the keyhole and became fixed there, right in *Fig. 2.14*. This shows that the easiest way for an arc is to occur between the electrode and "hot-spot" made by a laser. (Ishide et al., 1997)

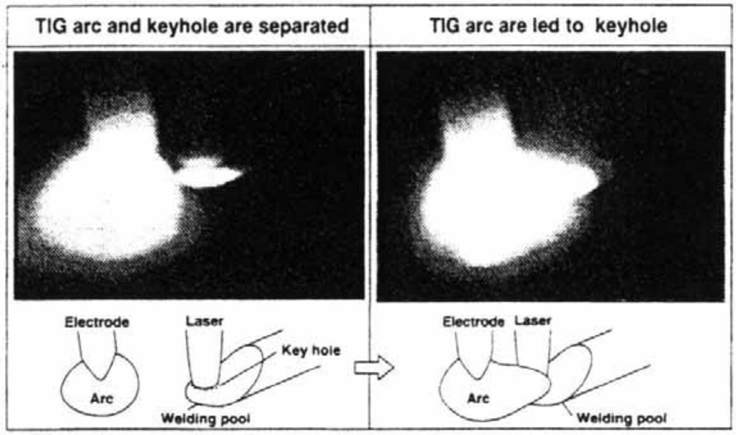


Figure 2.14. TIG and keyhole condition. Distance between the focus point and the electrode is 3 mm. (Ishide et al., 1997)

Another example of the stabilizing effect is shown in *Fig. 2.15*, which shows the bead appearances, macrostructure of weld beads and plasma behaviour during hybrid welding with a MAG and CO_2 -laser. It can be seen that a relatively small welding current of 60 A can hardly generate arc during plain MAG welding, whereas with hybrid welding a stable process and smooth weld bead are received. The arc stability can also be seen in the fluctuations of the welding current measured during the process. The process stability requires, that the distance between the laser spot and the electric pole of the arc, is within certain limits in order to gain a mutual plasma and stabilizing effect, as can be seen in *Fig. 2.15*. This is discussed in more detail in section 2.2.2. (Kutsuna and Chen, 2002)

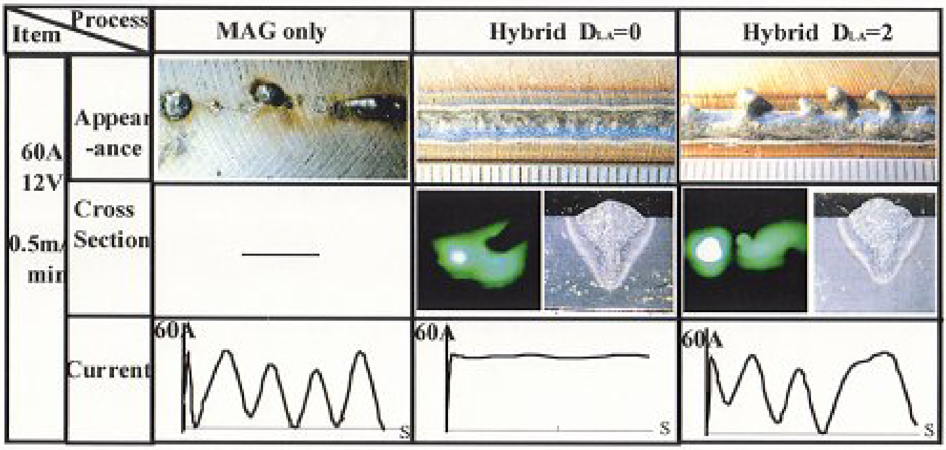


Figure 2.15. Comparison of the weld bead, cross-section and arc stability in hybrid welding with a MAG and CO_2 laser. D_{LA}= Distance between the arc impingement point and a point of the laser beam at the surface of the workpiece. (Kutsuna and Chen, 2002)

Transmission of the filler metal of MIG/MAG is an important factor when introducing it successfully to hybrid welding. A smooth molten droplet transfer must be formed in order to suppress the defects. (Minami et al., 2002) One excellence of the hybrid process is that smooth and small droplet filler metal transfer occurs, although MIG/MAG parameters are not in the level known for this kind of transfer in plain MIG/MAG welding. (Ono et al., 2002, Kutsuna and Chen, 2002, Makino et al., 2002) This can be noticed in experiments made by Ono et al, 2002. In those experiments the arc voltage was recorded both in arc welding and hybrid welding. It was noticed that in hybrid welding the arc voltage oscillated between 0–20 V at high frequency and the dip transfer of droplets from the wire took place in a cycle of about 10 ms. In contrast, the voltage during arc welding oscillates over a much wider range: 0–40 V and the drip transfer cycle time is significantly higher at 50–100 ms, *Fig. 2.16*.

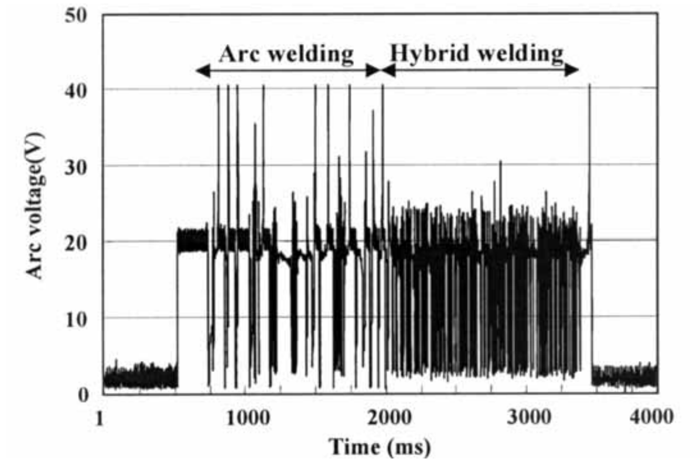


Figure 2.16. Time variation of arc voltage with and without laser radiation (Ono et al., 2002).

The reason why the dip transfer cycle time is shorter in hybrid welding can be explained as follows. In arc welding, the arc is maintained while the thermionic emission points (anode and cathode spot) are moving on the sheet, so the energy is widely dispersed, although some contraction of the arc exists due to the forces coming from the temperature differencies and magnetic field in plasma column. The conductive heat loss happens at the outer edges of the plasma column. This fall in temperature increases the gas resistance and forces the arc periphery inwards towards the hotter arc core so that a small arc contraction takes place especially at the anode. This causes an increase in current density and thus magnetic field strength. The magnetic field then produces an inward radial force on the arc plasma, which is balanced by a pressure gradient. Since the arc is not cylindrical, a pressure gradient along the axis of the arc is also produced, which induces a gas flow, i.e. the anode plasma jet. This gas flow sucks in surrounding cooler gas into the arc, causing further cooling and further arc contraction. The contraction of the arc is more pronounced in hybrid welding because of the hot plasma core superimposed by the laser beam and thus higher differencies in temperature in arc plasma column. (Steen, 1980, Ono et al., 2002)

During hybrid welding the arc is discharged from the laser radiation point at a diameter of about 1 mm, which squeezes the arc into a narrow range and concentrates the energy, although above-mentioned contraction is more pronounced at the anode spot. Therefore, the wire is easily melted, and the arc length is short (potential gradient is high), so the droplets become small and are transferred to the base metal at a high frequency. (Ono et al., 2002) The arc discharge mechanism for arc and hybrid welding are shown in *Fig. 2.17*.

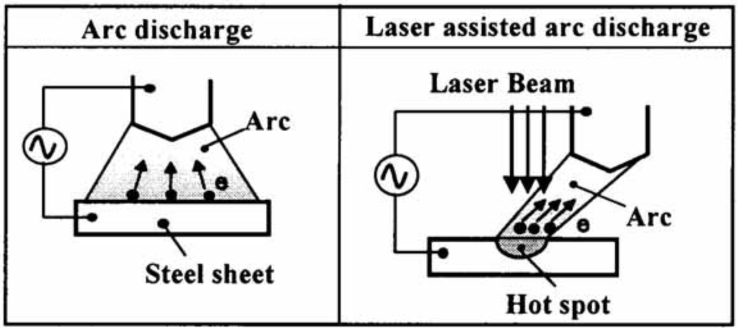


Figure 2.17. The mechanism of arc discharge with and without laser radiation (Ono et al., 2002).

Fig. 2.18 shows typical cross-sections of hybrid welds. It has been noticed, that the penetration depth is still related to the keyhole formation dominated by the laser beam characteristics and the laser power, although mainly the advantages of the hybrid process arises from the mutual effect of the processes. From the cross-sections this can be seen: The lower part of the weld profile is typically laser related and the wide upper part of it is MAG related.

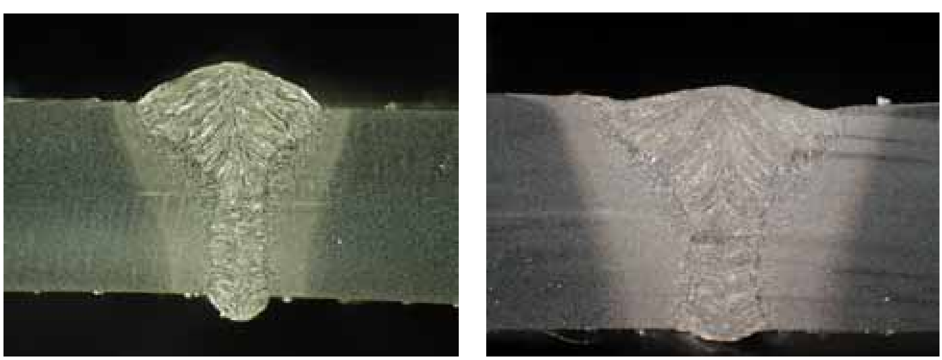


Figure 2.18. Typical cross-sections of hybrid welds in 6 mm mild steel with a CO_2 laser and MAG. Laser power 4.8 kW, distance D_{LA} 3 mm, welding speed 1.2 m/min, arc current 180–230 A, arc voltage 32–35 V. (Fellman, 2002)

2.2.2 Parameters

In hybrid welding the number of variable parameters grows through coupling the processes. According to the nature of the hybrid process, careful consideration has to be given to the common and individual parameters, because they define, whether the arc is helping the laser or vice versa. Consideration is based on the material and its thickness, laser power available, joint geometry and tolerances, mechanical properties of the joint wanted etc. The situation, where the laser accounts for the penetration and the arc the gap bridging ability and higher welding speed, is normally required. Some applications are also introduced, in which the laser acts more like an extra heat source in order to stabilize the arc. One disadvantage of the hybrid process is that parameters of the individual processes cannot necessarily be directly inferred for successful hybrid welding.

Distance between the laser spot and arc, D_{LA}

The distance, D_{LA}, between the laser spot and discharging point of the arc on the workpiece is an important factor in hybrid welding. The best results, due to a mutual effect of both processes, are received when the plasmas of individual processes are combined. This means that the distance, D_{LA} should be within certain limits. If the D_{LA} is large, the plasmas are separated and the phenomenon is more or less a combination of processes. However, the arc and especially the filler metal introduced, should not disturb the keyhole made by the laser. This means that the arc with the filler metal should not be introduced straight to the laser spot. With TIG and plasma welding the situation is different. By using the same irradiation point, some advantages are received. (Ishide et al., 1997, Dilthey and Weischemann, 2000, Andersen and Jensen, 2001, Jokinen et al., 2002)

As can be seen in *Fig. 2.19*, the penetration decreases if the arc and beam irradiation position are completely unified, but increases if the beam is set at a point of 2 mm forward or backward from the arc in Nd:YAG and MIG welding. If both the beam and the arc are separated by about 4 mm, penetration decreases again. This suggests, that the laser energy is used in melting the wire in the formation of the keyhole in the case where the same point is aimed at. So, when the laser irradiation position is at the same point as the discharging pole of the arc, attention needs to be paid to the generation and maintenance of the keyhole, because there is a lot of deposited filler metal. In other words, when an attempt is made to generate a deep keyhole where there is too much deposited metal, its generation and maintenance become difficult and cause the reduction in the depth of penetration and instability of the keyhole. Displacing the laser and arc irradiation point is shown to be an effective way to achieve deeper penetration, because the molten pool is smaller, so the generation and maintenance of the keyhole is easier and therefore penetration increases as well as defect-free welds are produced. The results seen by high speed video of arc phenomena are shown in the same *Fig. 2.19*. As can be seen, the best results, in the case of penetration, are received when plasmas of separate processes are mutually influenced and also when the arc is not disturbing the keyhole made by the laser. When the laser irradiation point is far from the molten pool of the arc, the molten pools are separated and mutual effects of the processes are no longer valid. (Abe and Hayashi, 2002, Ishide et al., 2002)

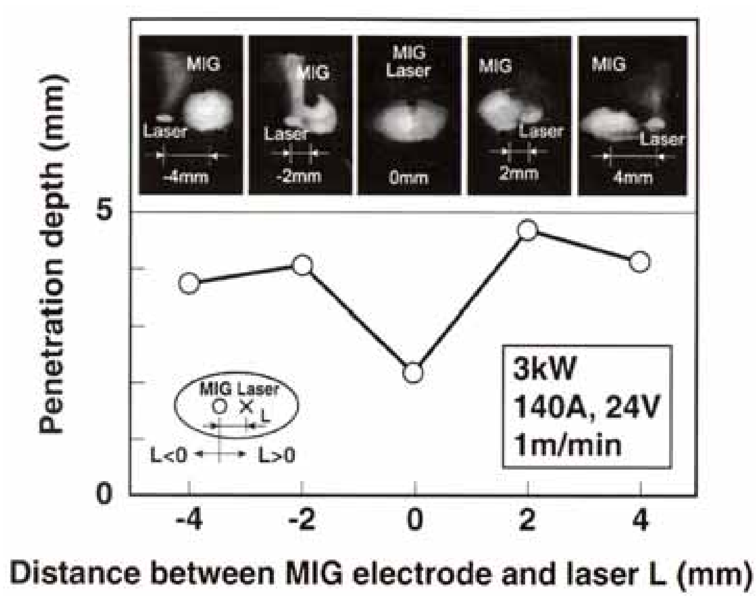


Figure 2.19. The effect of the MIG-Nd:YAG laser distance on the penetration depth (Ishide et al., 2002).

When TIG welding without filler metal is introduced with laser welding, phenomenon of the keyhole and molten pool is different. This has an influence on the optimum distance D_{LA}. *Fig. 2.20* shows how the molten pool of coaxial

TIG-Nd:YAG welding becomes larger than the welding by plain Nd:YAG due to the increassed energy deposited. It can also be seen that the keyhole diameter is expanding 1.5 times larger, which corresponds that the TIG arc is not disturbing the generation and maintenance of keyhole unlike in MIG/MAG welding when the filler metal is introduced. (Ishide et al., 2002)

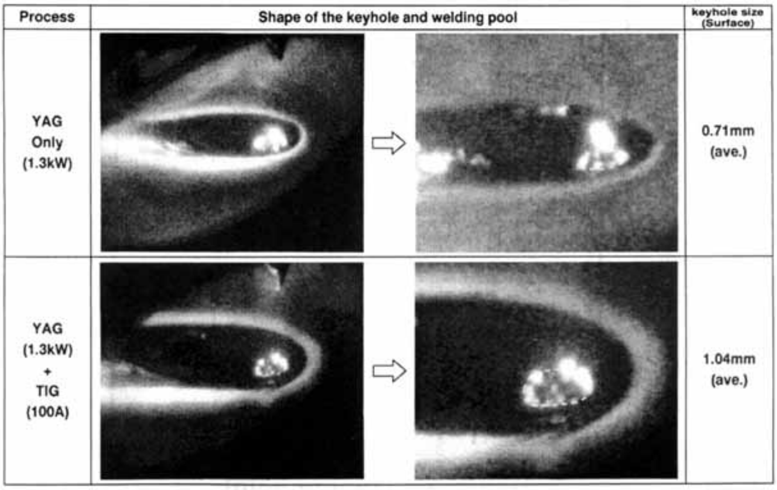


Figure 2.20. The shape of the keyhole and weld pool in TIG+Nd:YAG laser welding (Ishide et al., 2002).

The value D_{LA} corresponding to a deeper penetration is related to such parameters as laser type and power used, arc type, arc and molten pool size, which in turn depend on welding current, voltage and welding speed. Owing to this, different values are presented in the literature to be the optimum value for D_{LA}. The leading principle in MIG/MAG hybrid welding is still that penetration decreases when D_{LA} is zero and is increasing with increasing D_{LA} to a certain distance. When the distance is increased excessively, the plasmas are separated and the penetration is coming only from the laser power and no mutual effects of the hybrid process exists. With TIG and plasma hybrid welding, when the filler metal is not introduced, the distance is better to be zero. (Ishide et al., 1997, Kutsuna and Chen, 2002. Abe and Hayashi, 2002) The studies of Steen, 1980 indicate that in successful and effective hybrid welding considerable penetration of the keyhole by the arc is probable.

Torch orientation

According to the above-mentioned, success of a hybrid process is dependent greatly on the irradiation points of both the laser beam and the arc. When using TIG hybrid welding without filler metal, the placement is more flexible. When the TIG electrode is placed in front of the Nd:YAG laser, the TIG arc partly burns into the keyhole and partly pinches the fresh metal surface. Thus, the arc produces a shallow melt pool in front of the laser-generated keyhole. Absorption of the laser becomes better and the keyhole diameter grows. When the TIG electrode is behind the laser beam and impinges on the molten pool, the arc is more difficult to stabilize and the molten metal easily sticks to the electrode tip. One way to overcome this is to place the TIG electrode sligthly away from the centerline of the weld. It was found that when this was done better welds were achieved, when TIG was behind the laser beam. (Gu and Mueller, 2001) The same effect was found in constant penetration when using a special, coaxial optical arrangement *Fig. 2.21*. The penetration is not affected by the spot arrangement vertical or parallel to the welding direction. (Ishide et al., 2002)

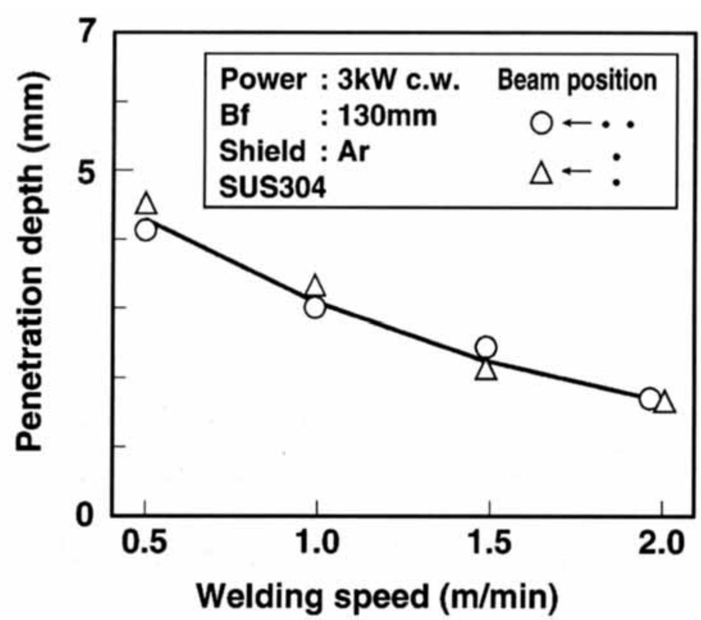


Figure 2.21. The effect of beam focusing condition on penetrations in hybrid welding with a TIG and Nd:YAG laser (Ishide et al., 2002).

The situation differs slightly when introducing filler metal i.e. using MIG/MAG welding. As in laser welding with filler wire, both the direction of the arc torch/filler metal feeding; trailing or leading, can be used and has been used. Rather small differences have been reported when changing the welding direction and according to that, the reported results are often in conflict. For example, an improvement of 10% in penetration has been noticed when welding 12 mm thick C/Mn steel and having the MAG -torch behind the laser beam. Better disparity has been noticed in the shape of the weld produced, *Fig. 2.22*. (Hyatt et al., 2001, Nielsen et al., 2002, Jernström et al., 2002)

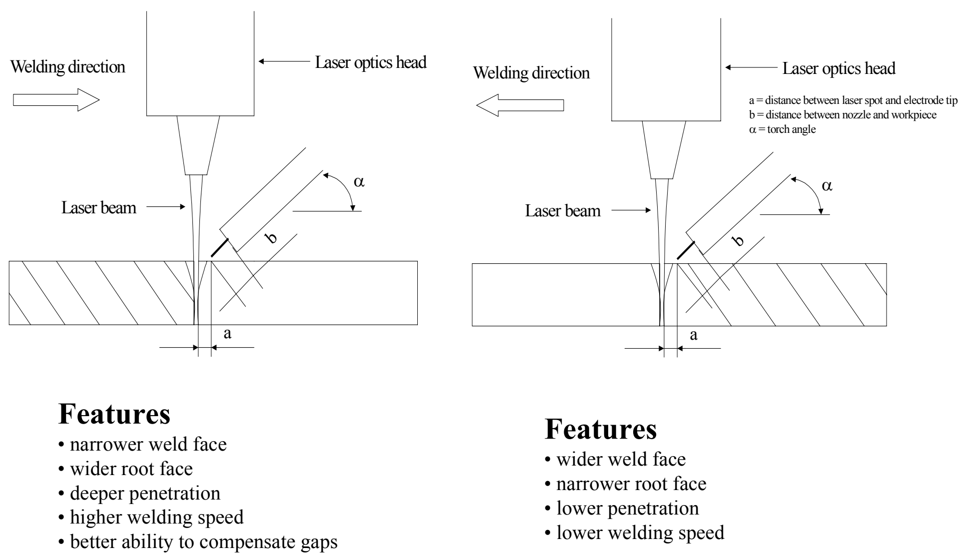


Figure 2.22. Differencies in the welds produced when the welding direction has been changed (Jernström et al., 2002).

Parameters of the arc process

The main parameter in the case of MIG/MAG welding, which affects on the hybrid process and is controlled by the arc welding machine, is the filler wire feed rate. Using *Equation 2.1*, which is used for laser welding with filler wire, the required filler wire feed rate to fill the gap can be roughly calculated. Nowadays welding machines have synergic control, which means that according to the amount of filler metal, arc voltage and current are adjusted automatically. It has been reported that these parameters are quite good for a successful process, although a slight decrease in arc voltage has also been reported to enhance the process. (Jokinen et al., 2002, Schubert et al., 2002)

Depending on the shape of the weld required, arc current and voltage can be tuned: Increasing arc power (i.e.voltage) at constant wire feed speed and laser power, increases the bead width, especially in the upper region of the weld. Although a slight increase in penetration is achieved when increasing the arc current, generally the effect decreases with increase in current. This effect may be the result of the laser light being partially absorbed or deflected by the additional arc plasma generated at higher current levels, especially in the case of the CO_2 -laser. (Hyatt et al., 2001, Walz et al., 2001)

One interesting point in arc parameters is pulsing of the arc current. This is reported to affect the shape of the weld (shallower), quality (better due to a spray transfer of filler metal) and welding speed, which can be slightly increased. (Makino et al., 2002, Jernström et al., 2002, Ueyama et al., 2002)

Process gases

Helium gas shielding is typically employed during laser welding, due to its low ionization potential and hence, reduced tendency to form plasma, which disturbs absorption of the laser power to the joint. The disadvantage in using helium is the cost of it. In MIG and TIG welding argon is normally used as a shielding gas. In a pure argon atmosphere, a MIG arc is not very easily stabilized and the bead formation is not stabilized, because of the shortcircuit mode of filler metal transfer. With MAG welding argon is usually used with a small amount of oxygen or carbon dioxide in order to aid the spray mode filler metal transfer and thus a more stable process. In a hybrid process, the above-mentioned means careful optimizing of the shielding gas mixture. It has been reported that, up to 50% argon could be added to the shielding gas stream without excessive plasma formation and thus substantially altering the depth and width of the weld pool, *Table 2.2*. Experiments, in which oxygen has been added to the shielding gas to promote spray transfer of filler metal, have also been reported to be successful. The addition of 4.5% oxygen produces spray transfer conditions and far less spatter. (Hyatt et al., 2001, Walz et al., 2001, Fellman, 2002, Ishide et al., 2002)

Table 2.2. Bead-on-plate hybrid weld pool dimensions for Helium-Argon shielding gases (Hyatt et al., 2001).

Gas composition	Weld depth [mm]	Weld width [mm]	Aspect ratio
100% He	9.8	11.4	0.85
75% He + 25% Ar	9.5	11.8	0.80
50% He + 50% Ar	9.5	12.4	0.76
25% He + 75% Ar	7.5	14.1	0.53

According to the reports made from the gas tests with hybrid welding, a separate shielding gas nozzle is not needed even in the case of the CO_2 laser. Good results were gained when a certain gas mixture was fed from the nozzle of an arc torch at a certain pressure. When welding with a CO_2 laser with a power of 4.8 kW, the best gas mixture coming only from the gas nozzle of arc torch, was 40–50% helium and 2% carbon dioxide and the rest was argon. The flow rate of gas was set at 30 l/min. The amount of helium was found to be enough to prevent the excessive formation of plasma and thus its absorption effect on the laser beam. The amount of carbon dioxide was enough to smooth the weld bead to base metal. (Hyatt et al., 2001, Fellman, 2002)

2.2.3 Gap bridging ability

One of the main advantages of the hybrid process is the gap bridging ability compared to laser welding, *Fig. 2.23*. According to a rule of thumb, an air gap of 10% of plate thickness is allowed in laser welding without filler metal. This is a quite tight demand, especially when welding large structures, for joint manufacturing and also for fixtures, which place the parts to be welded and keep those in certain fixed position during welding. (Ishide et al., 2002, Salminen, 2001b)

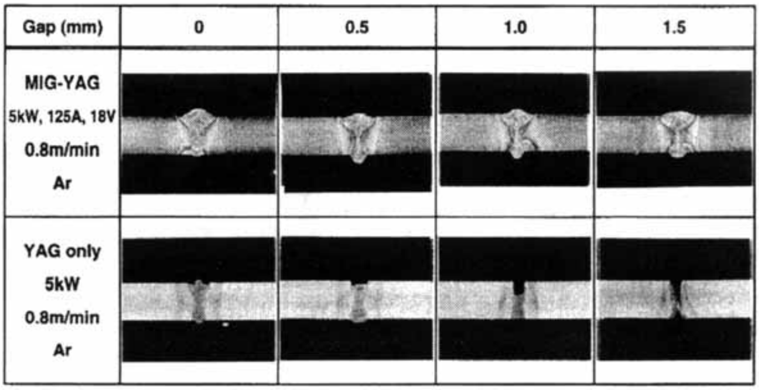


Figure 2.23. Comparison between MIG-YAG only in gap tolerance. Plate thickness of 6 mm. (Ishide et al., 2002)

When using filler wire, the changes on the joint tolerances can be overcome, but the process is not so efficient due to a lower welding speed. Hybrid welding has an advantage over the welding with filler wire, because the welding speed is greater. The gap bridging ability of these two processes is quite the same, the question is about the welding speed, *Fig. 2.24*. (Dilthey and Wieschemann, 2000, Salminen, 2001b)

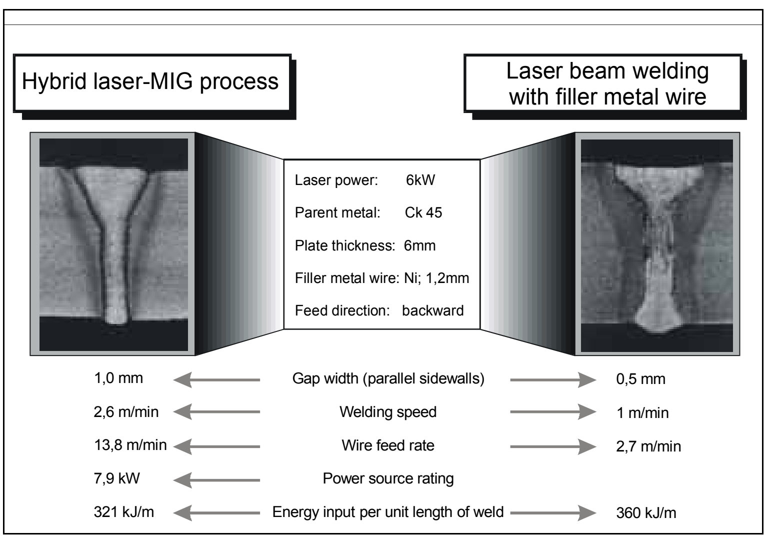


Figure 2.24. Comparison of laser welding with filler wire to the hybrid welding (Dilthey and Wieschemann, 2000).

Higher welding speeds have also been reported by Nielsen et al., 2002. In their experiments on C/Mn steel with a plate thickness of 12 mm, it was noted that if the air gap was smaller than 0.4 mm, extra energy from the arc was about 2–3 kW and the welding speed increased by about 15% compared to the laser welding with filler wire. When the air gap was between 0.5–1 mm, extra energy from the arc was 6–8 kW and the welding speed was 50–100% higher than with laser welding with filler wire.

The gap bridging ability in hybrid welding comes mainly from the filler metal fed to the process, which is a typical advantage of MIG/MAG welding. Still with MIG/MAG welding, a high penetration effect cannot be reached, *Fig. 2.25*. This part of the process comes from the laser and its keyhole welding effect. (Kutsuna and Chen, 2002)

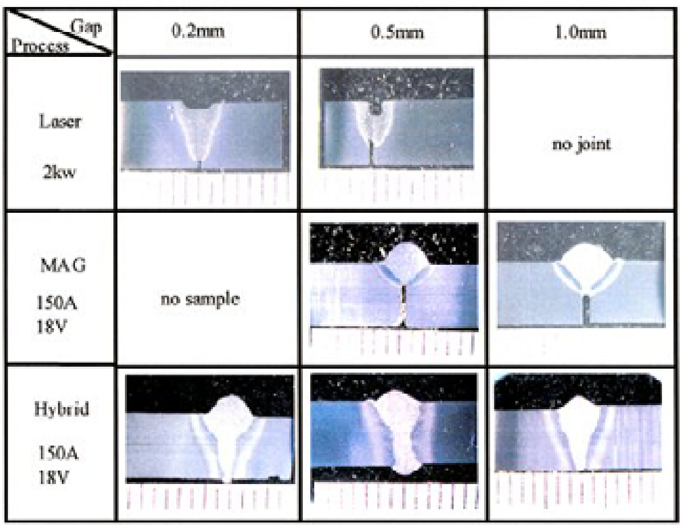


Figure 2.25. Cross-sections of weld bead obtained by three processes with different gaps. Plate thickness 6 mm. (Kutsuna and Chen, 2002)

Not only in the case of a butt joint, the air gap can be present when using hybrid welding. Also in the case of a lap joint, the air gap between the plates can be much higher than with plain laser welding, even as high as the plate thickness a sound weld bead can still be produced with hybrid welding. Also gap bridging ability has been noticed in the case of T-joints. (Gu and Mueller, 2001, Ono et al., 2002, Ishide et al., 2002)

2.2.4 Applicability for very thick sections and a narrow groove

Hydrid welding has been introduced mainly in applications where plate thickness allows single pass welding and thus also experimental work has been focused on single pass welding, *Fig. 2.26(a)*. According to the experiments published, this means plate thicknesses of up to 12–16 mm. The limiting factor in the plate thickness in single pass welding is the power of the laser. Naturally, with high power lasers, it is possible to weld a thickness far over the above-mentioned. But also with medium power lasers, the welding of very thick steel plates is possible by using a groove between the plates to be welded and a multi pass welding technique, *Fig. 2.26(b)*. Hybrid welding gives an excellent opportunity to use medium power lasers for thicker sections, asin laser welding with filler wire. In this case the laser does not have to be very powerful and this means cost reductions and still more effective welding can be done compared to multi pass arc welding, *Fig. 2.26(c)*. (Abe et al., 1997, Hyatt et al., 2001)

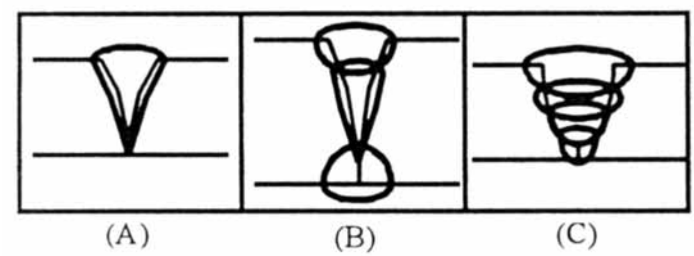


Figure 2.26. A typical application of hybrid welding and conventional arc welding of thick plates (Abe et al., 1997).

According to Abe and Hayashi (2002), the principle features of hybrid welding for thick plates are:

1. Deeper penetration than with plain laser welding.
2. The arc electrode supplies molten metal to the gap and the groove.
3. The laser plasma stabilizes the arc. This effect is particularly important for high speed welding with a narrow groove.
4. The laser plasma also leads the electrical pole of the arc to a deeper point in the groove of the base metal.

When welding of thick plates is executed by arc welding, multi pass welding is conducted by making grooves. These grooves are usually as narrow as possible to improve productivity. However, when the groove is too narrow, the arc does not reach the root and causes lack of penetration. In hybrid welding, the existence of a laser enables the arc to be extended to a deeper area than by arc welding only. *Fig. 2.27* shows the bead geometry formed when hybrid welding is applied to multi pass welding of 20 mm thick steel plates. The bead geometry formed by laser welding in the first pass and hybrid welding in the 2nd pass is compared with that formed by arc welding only. Whilst the bead to which hybrid welding is applied, has the first and second pass fused, it is difficult to prevent incomplete fusion in arc welding, even when the arc power is increased. Fusion is completed in hybrid welding presumably because the laser plasma extends the root to a deeper area of the groove. In other words, to enable the arc to reach areas of the same depth, grooves can be narrower in hybrid welding than in plain arc welding. And this affects the productivity very strongly. (Abe and Hayashi, 2002)

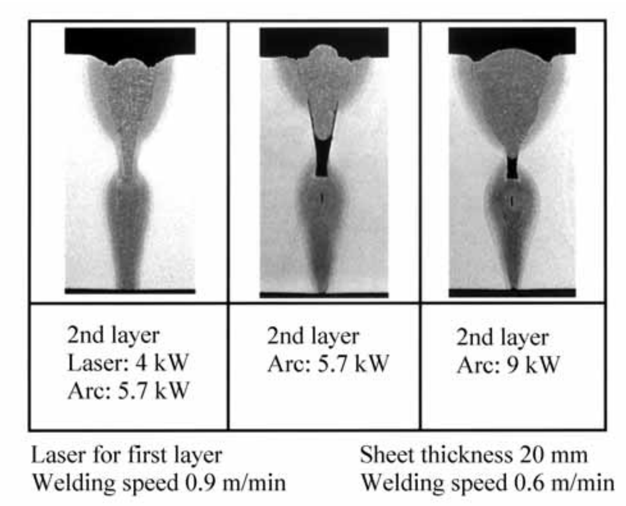


Figure 2.27. Cross-sections of the welds produced by hybrid welding (CO_2+MAG) and arc welding (MAG) only (Abe and Hayashi, 2002).

Often the groove geometry applied in multi pass hybrid welding is partially grooved V, *Fig. 2.28*. The root face of the joint is normally adjusted to the thickness, which can be welded with plain laser welding without filler metal. If filler metal is fed in the first weld, a certain air gap is maintained between the root surfaces, *Fig. 2.28*. The upper region of the groove is filled by a second pass made by hybrid welding. The groove angle is adjusted depending on the thickness and hybrid parameters used. According to the productivity of the process the angle should be kept as small as possible without weld defects, as in *Fig. 2.27*. Thus, also in hybrid welding, the critical thing is that both laser power and arc power reaches the bottom of the groove. The groove angle can be very small and still allow a laser beam to reach the root of the joint, because of the fine focusing angles. It is more difficult for the arc to reach the bottom of the groove reliably. One helpful thing is discussed in section 2.2.1. Namely, the stabilizing, guiding and contraction of the arc due to the laser beam and especially the beam irradiation point. This is why narrower grooves can be used in hybrid welding than in plain arc welding. (Eboo et al., 1978, Steen, 1980, Abe and Hayashi, 2002, Makino et al., 2002, Ishide et al., 2002, Ono et al., 2002)

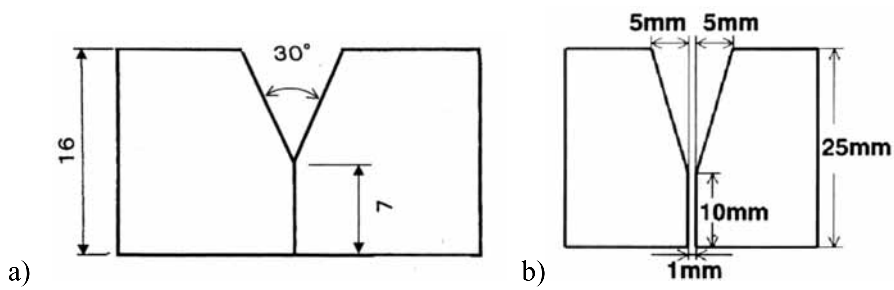


Figure 2.28. An example of the groove geometry often used in multi pass hybrid welding. A root weld without filler metal (a), a first weld with filler metal (b). (Makino et al., 2002, Ishide et al., 2002)

Fig. 2.29 shows cross-sections of the weld with differences in groove angle and laser parameters. Groove geometry is a single bevel, a partially grooved V butt joint and a weld that consists of two passes: first with a plain CO_2 laser and the second by hydrid welding. As can be seen, a groove angle of 20^o is not enough for the arc to reach the tip of the groove and a lack of fusion is observed. With a 25^o groove angle, however, it can be welded without defects between the passes independent of laser power. (Minami et al., 2002) In hybrid welding (5.5 kW CO_2 laser and MAG) experiments with 25 mm thick steel, the optimum groove was defined to be a partially grooved V with a root face of 8 mm and a groove angle of 45^o. Narrower grooves from 7 up to 30 degrees were also tested, but pronounced incomplete penetrations were noticed. (Hyatt et al., 2001) When the thickness was 16 mm, a 30° groove angle in a partially grooved V joint was reported to produce sound welds without weld defects coming from the incomplete penetration. (Makino et al., 2002)

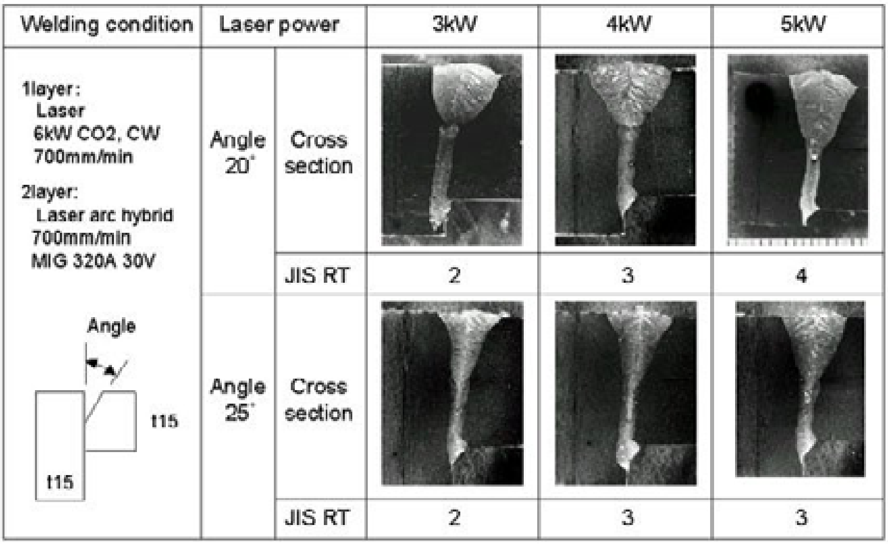


Figure 2.29. Cross-sections of the welds with differences in groove angles and laser parameters (Minami et al., 2002).

2.2.5 Differences between CO_2 and an Nd:YAG laser

It is well known, that the biggest difference between CO_2 and an Nd:YAG laser is the wavelength of beams emitted. While it is 10.6 μm in the case of a CO_2 laser, Nd:YAG laser beam has a wavelength of 1.06 μm. This means a difference in absorption of the laser beam to the material. The best example of this is the difference in the beam guidance from the laser to the workpiece. In the case of an Nd:YAG laser, the beam can be delivered flexible via an optical fibre almost without loss, while transfer of a CO_2 laser beam is handled through an optical mirror system.

A more significant difference between CO_2 and Nd:YAG laser, from the point of view of welding, is the absorptivity of the vaporized metal above the keyhole. This plume is formed from the vaporized metal ejected from the keyhole. There is an established practice, as in this thesis, in the field of laser welding to call that metal plume as a plasma, although it has been reported that the plume is not real, ionised plasma in the case of Nd:YAG laser welding. Greses et al., 2002, have shown that the vapour ejected from the keyhole in Nd:YAG laser welding is a high-temperature thermally excited gas rather than a partially ionised plasma and the beam attenuation is dominated by scattering. In the measurements, up to 40% attenuation of the Nd:YAG probe laser was noticed when it was arranged horizontally incident across the plume generated by the high-power (8 kW) Nd:YAG laser.

On the other hand it has been reported that an Nd:YAG laser beam having quite a short wavelength is not so much absorbed by the plume as the beam of the CO_2 -laser. This affects hybrid welding and especially with narrow grooves. In the experiments made by Ishide et al 2002, with an Nd:YAG laser and TIG welding, it was found that there is a very small difference between the beam power in the joint without arc or with arc, when also laser-induced plume existed above the keyhole. Concerning the electron density of the TIG arc and plume, the measured results show an electron density of 10^{16}–10^{17} /cm^3. (Ishide et al., 2002) This is some 100 times smaller than is reguired to block a Nd:YAG beam by inverse bremsstrahlung to a negligible level. This also implied that beam absorption does not affect on penetration and thus it was reported that the beam absorption by arc and laser plume might be even ignored. Nonexistent absorption of the laser induced plasma and the arc itself, affects on the hybrid process with an Nd:YAG laser. Distance D_{LA} can be shorter and thus even more heat input takes place through the keyhole and plate thickness. Naturally such case differs when introducing filler metal with the arc i.e. MIG/MAG. Then the beam is absorbed also by the molten transfer of filler metal. (Abe and Hayashi, 2002, Nakajima et al., 2002, Ono et al., 2002)

Existence of laser induced plasma and its absorptivity of a CO_2 -laser beam in hybrid welding has been reported by Nakajima et al., 2002. In the experiments radiation coming from the plasma was detected during hybrid welding with a 5 kW CO_2 -laser and 10 kW MIG. By changing the distance D_{LA} from 0 up to 20 mm, different behaviour of the plasma was seen, *Fig. 2.30*.

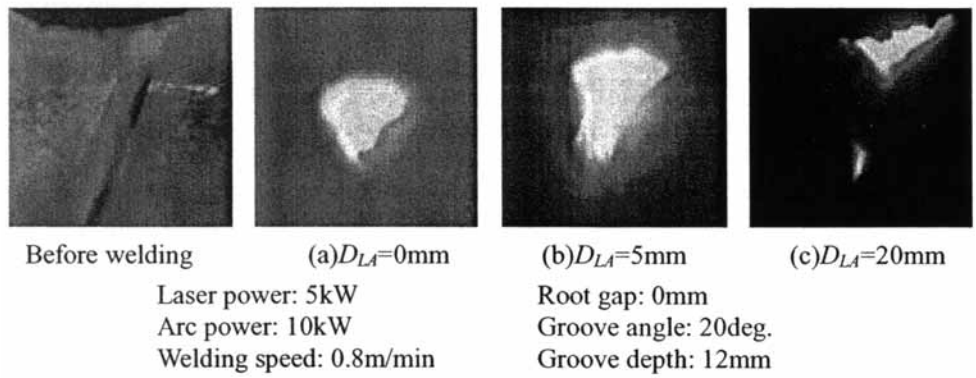


Figure 2.30. Radiation observed by a CCD camera from the hybrid process (Nakajima et al., 2002).

From images in *Figs. 2.30 and 2.31* the following items were determined (Nakajima et al., 2002):

1. D_{LA} = 0 mm: The radiation appears mainly over the surface of the material and its temporal change is low. This position is the same as that with MIG welding and no laser plasma in the groove can be seen. The above results suggest that the laser is absorbed by the arc plasma and the welding zone is identical to that with MIG welding.

2. D_{LA} = 10 mm: The radiation appears over the surface and on the upper region of the groove. Both positions are adjoined in the vertical and the travelling direction. As for the temporal change, the radiation in the groove becomes deeper with time.

3. D_{LA} = 20 mm: The radiation appears over the surface and in the lower part of the groove, where it separates in the vertical and travelling directions. It seems that MIG welding and the laser welding generate plasma independently. The temporal change is low.

In the same experiments (Nakajima et al., 2002), it was noticed that the wider the groove opening width was, the deeper the radiation from plasma appeared, *Fig. 2.31*. To sink the arc plasma into the groove effectively without radiation on the surface of the material, it was desirable for the groove opening width to be more than 4.2 mm, *Fig. 2.31*.

Groove opening width (mm)	2.5	3.5	4.2	5.3
Material surface →				
Groove angle (deg.)	15	20	20	30
Groove depth (mm)	10	10	12	10
Laser power: 5kW Arc power: 10kW Welding speed: 0.8m/min Root gap: 0mm D_{LA}: 10mm				

Figure 2.31. Typical radiation by changing the groove opening width (Nakajima et al., 2002).

3. Experimental procedure

3.1 Laser and auxiliary equipment

Welding experiments were made with a 3 kW Nd:YAG laser with fiber optic beam transfer (HAAS – LASER GmbH model HL 3006 D). The diameter of the optical fiber was 0.6 mm, which together with the focusing system of the resonator gave a beam parameter product of 25 mm*mrad. The full 3 kW laser light power was used in the experiments and it was measured at the surface of the workpiece, *Fig. 3.1*. A focusing optic with a focal length of 200 mm was used in each of the test runs, which gave a focal point diameter of 0.6 mm and focusing angle of 6.12^o, *Fig. 3.2*.

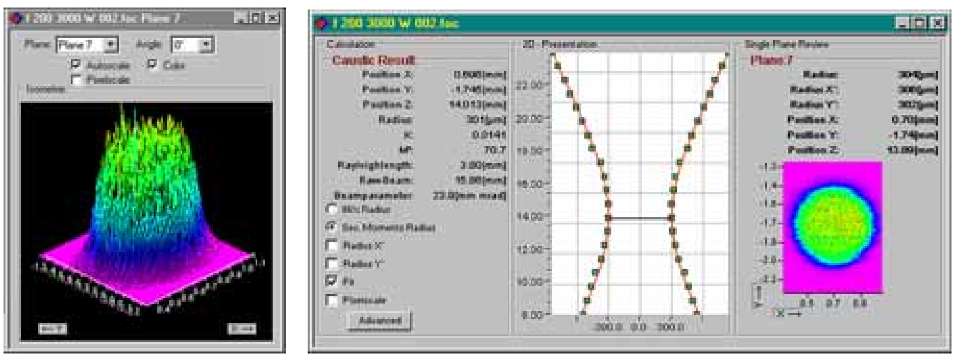
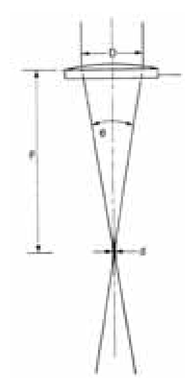


Figure 3.1. Profile and power of the laser beam measured using Primes focusmonitor.



D = 22 mm

F = 200 mm

$\theta = 6.12^o$

d = 0.6 mm

Figure 3.2. Geometry of the focused laser beam used in the experiments.

3.1.1 Filler wire feeder

Filler wire was fed to the process by the wire feeder (CRC-Evans, Model WF-100). The set-up and nozzle geometry can be seen in *Fig. 3.3*. To ensure accurate positioning of the filler wire, the handling equipment was built and installed at the welding head. The nozzle handling equipment allowed all relevant adjustment of the filler wire e.g. feed angle and point of interaction between the laser beam and wire.

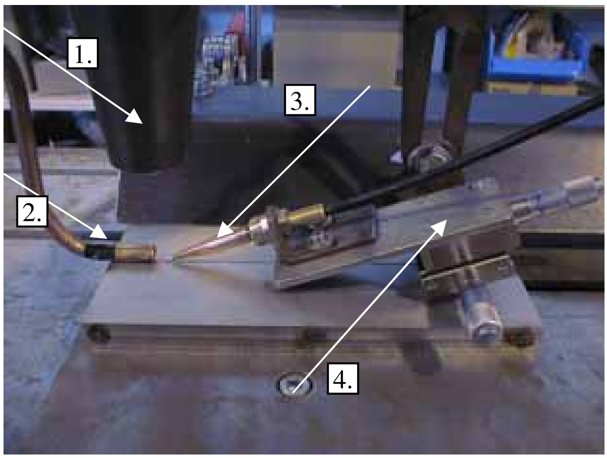


Figure 3.3. The set-up in filler wire experiments. In figure 1) Optical laser head, 2) Shielding gas nozzle, 3) Filler wire nozzle, 4) Adjusting plate of filler wire feed nozzle.

3.1.2 MIG machines

Two different kinds of MIG machines were used in the hybrid experiments, with single pass Kemppi Kempomat 180 and with multi pass Kemppi Pro 5200 Evolution. The former machine was equipped with a simple synergetic adjustment of the arc current according to the filler wire feed rate. The latter one, which was used in the multi pass experiments, was totally synergetic to its adjustments. The material, the filler wire and its diameter and shielding gas were selected, and then based on this data, the machine adjusted the arc current and voltage. After the welding sequence, values were readable from the screen.

In the hybrid tests, the torch of the MIG was placed at the laser welding head with handling system allowing movements necessary for changing interaction parameters, *Fig. 3.4/A*. The MIG contact nozzle was modified to the shape shown in *Fig. 3.4/B*. Shielding gas was guided both via the MIG torch and the extra nozzle.

A) 

B) 

Figure 3.4. The set-up in hybrid welding tests and numbered (1–4) adjusting movements allowed by it A), and a detail picture from the interaction point B).

3.2 Materials

Materials used in the experiments were two austenitic stainless steels, EN 1.4406 (AISI 316LN) and EN 1.4307 (AISI 304L), which were used during experiments according to *Table 3.1*. Filler wires used in the experiments were chosen according to the base material: AWS 5.9 ER 316 LSi (ESAB mark name OK 16.32) and AWS 5.9 ER 308LSi (ESAB mark name, OK 16.12). The diameter of the filler wire was kept at 0.8 mm for each experiment.

Table 3.1. Chemical composition of the materials used in the experiments. (Cast analysis for steels and nominal analysis for filler wires.)

% / Material	C	Si	Mn	P	Mo	S	Cr	Ni	N	**Experiment used in**
AISI 316LN	0.017	0.4	1.2	0.031	2.59	0.001	17.2	12.4	0.17	Single pass
OK 16.32	0.025	0.8	1.8		2.7		19	12		Single pass
AISI 304L	0.017	0.33	1.52	0.025			18.2	8.2	0.07	Multi pass
OK 16.12	0.025	0.8	1.8				20	10		Multi pass

Both argon and helium were used as a shielding gas. The shielding gas was introduced to the filler wire experiments via an extra nozzle, *Fig. 3.3*. In the case of the hybrid experiments, both gas nozzles (extra nozzle and MIG torch) were used, *Fig. 3.4*.

3.3 Single pass experiments

3.3.1 Laser welding with filler wire

In single pass welding experiments, 6.5–6.9 mm plates were welded with an air gap of 1 mm. Plates were made by laser cutting and milling in order to justify the accuracy of the air gaps. Plates to be welded were tack welded by TIG to a backing plate in order to hold the plates to prevent distortions and also to ensure an exact 1 mm air gap, *Fig. 3.5*.

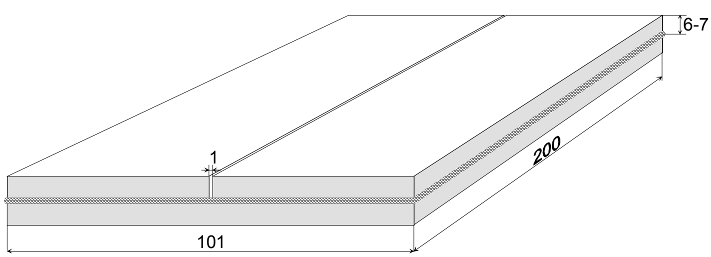
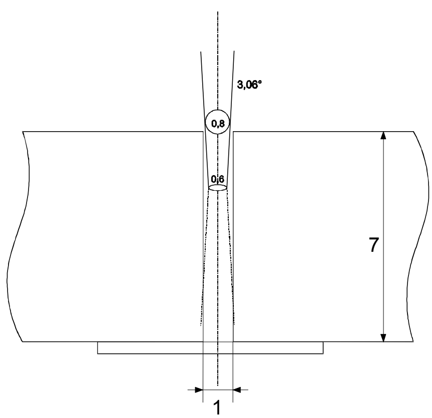


Figure 3.5. Configuration of the test pieces used in the single pass welding tests with filler wire, (values in mm).

By the Taguchi method with an orthogonal matrix L9 the effects of the wire feed rate, feed angle, focal point position and position of the laser beam and filler wire were studied, *Table 3.2*. In the orthogonal matrix L9, four different factors were varied in the three levels. The other parameters were kept constant, *Fig. 3.6 and Appendix 1*. As a result of the Taguchi test runs, the penetration of the welds with a welding speed of 0.5 m/min and the maximum welding speed with full penetration, were chosen, (Karjalainen, 1990).

Table 3.2. Factors and their values in the single pass TAGUCHI experiment with filler wire and an Nd:YAG laser, Appendix 1.

Factor			**Levels**		
			1	**2**	**3**
A	Wire feed rate, W_R	m/min	v_L-10% v_L	v_L	v_L+10% v_L
B	Wire feed angle, α_W	o	20	40	60
C	Focal point position, f	mm	-2	0	2
D	Interaction point of the laser and filler wire, W_Z	mm	-2	0	2



Laser power, P_L	3 kW
Shielding gas	He, 14 l/min
Focal length, F	200 mm
Focal point diameter, d	0.6 mm
Diameter of filler wire, d_W	0.8 mm

Figure 3.6. An example of the set-up in a single pass TAGUCHI experiment and constant parameters used. Set-up conditions; wire feed rate -10% v_L, feed angle 20^o, focal point position -2 mm, interaction point of laser and filler wire 2 mm, Appendix 1.

3.3.2 Hybrid welding

In single pass hybrid experiments, 6.5–6.9 mm thick austenitic stainless steel AISI 316LN was used with a butt joint configuration. Straight vertical groove surfaces were laser cut and after that milled in order to certify the accuracy. The air gap between the plates to be welded was adjusted to 1 mm by tack welding with TIG. *Table 3.3.* shows the constant and varied parameters used in the experiments.

Table 3.3. Constant and varied parameters in single pass hybrid experiments.

Constant parameters	Laser power, P_L [kW]	Focal length, F [mm]	Angle of torch, α_t [°]	Shielding gas [l/min]	
	3	200	40	He, 18 l/min	
Variable parameters	Wire feed rate, W_R [m/min]	Welding speed, V_W [m/min]	Focal point position, f [mm]	Torch orientation, D_t	Distance, D_{LA} [mm]
	7.2–9.7	0.5–0.9	0, -1, -2	leading/ trailing	-2, 0, 2

3.4 Multi pass experiments

3.4.1 Laser welding with filler wire

In order to weld thicker sections, multi pass welding with filler wire was introduced with a narrow groove. Parameters received from previous single pass tests were used as a reference to use effective parameters for filling the groove. With multi pass welding it is very critical that both the surface of the previous pass and also the surfaces of the groove at the point of welding are properly melted and so that the filling is still effective.

The groove angle and the geometry used were the result of the shape of the beam. All grooves used in the experiments were the shape of a partially grooved V with a parallel root face of 4 mm, *Fig. 3.7*. By using this groove geometry it was easy to control the beam so that it arrived at the bottom of the groove in order to melt the surface of the previous pass and also the surfaces of the groove. By using a 200 mm focusing optic the focusing angle was 6.12^{O}, that was why a groove angle of 8^{o} was the minimum that was used.

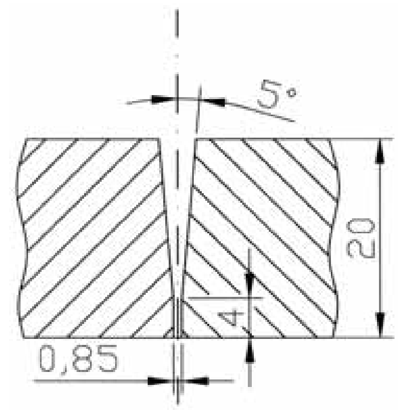


Figure 3.7. An example of the groove geometry used in the filler wire experiments.

According to the results achieved from the previous experiments, the root weld was first welded with the parameters shown in *Table 3.4*. With this procedure it was ensured that proper melting of the root surfaces occurred.

Table 3.4. Parameters of the filler wire laser welding for root weld.

Welding parameters	
Laser power, P_L	3 kW
Focal distance, F	200 mm
Wire feed rate, W_R	4.5 m/min
Diameter of the filler wire, d_W	0.8 mm
Focusing distance from the surface, f	-15 mm
Interaction point, W_Z	-2 mm
Welding speed, V_W	0.5 m/min
Filler wire feed angle, α_W	40^{o}
Shielding gas and flow rate	Helium, 14 l/min

First filling pass

The welding experiments for the first filling pass was made with the arrangement shown in *Fig. 3.8*. All grooves were milled to the shape of the partially grooved V with the parallel root face of 4 mm. The upper side of the groove was milled according to the test program with the groove angles of 8^o, 10^o and 12^o. Testpieces were tack welded consisting of a 1 mm air gap between the root faces. After that, the root passes were welded, *Table 3.4*.

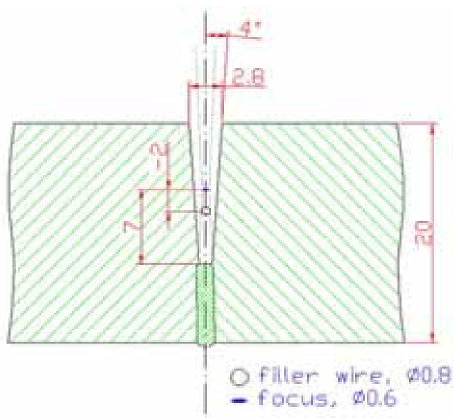


Figure 3.8. An example of the set-up in the welding experiments for the first filling pass. Set-up conditions; groove angle 8^o, wire feed rate 35% less than groove volume v_L , focal point position 7 mm, interaction point of the laser and filler wire -2 mm, Appendix 2.

After welding the root passes, every groove used in the experiments was measured in order to be certain about the fixed parameters. The focal point position of the laser beam was then adjusted according to the bead surface of the root weld. It was raised from that 5, 6 or 7 mm.

In the experiments, other varied parameters were the filler wire feed rate and the interaction point of laser beam and wire in the vertical direction, see *Table 3.5 and Appendix 2*. The wire feed rate was calculated according to the groove volume starting from -10% up to -35% of the groove volume. It has been noticed in previous welding experiments that according to the quality of the welds, the amount of filler wire fed cannot be too high and it should be kept at a moderate level according to the groove volume. The groove volume was calculated by the aid of the groove geometry measurements. The upper limit, which was used in calculations, was the focal point position used in individual experiment.

From previous single pass welding experiments it was noticed that filler wire should be pointed under the laser beam in order to stabilize the process. That is why in this experiment the interaction point was placed zero, two or four millimeters below the focal point position.

Table 3.5. Varied welding parameters in the filler wire experiments for the first filling pass, Appendix 2.

Parameter	Values		
Groove angle, β [^{o}]	8	10	12
Focal point, f [mm]	5	6	7
Feed rate, W_R [m/min]	v_L-10%v_L	v_L-20%v_L	v_L-35%v_L
Interaction point, W_Z [mm]	-4	-2	0

All the constant parameters used in the experiments for the first filling pass and their values are listed in *Appendix* 2.

Thicker sections

Knowledge of the process, received from the above-referred experiments, was used in the experiments on thicker sections. Filler wire experiments were made up to a thickness of 35 mm with a groove angle of 8^o and 10^o. In order to reduce time in groove manufacturing, some of the preliminary testpieces were made according to *Fig. 3.9*. According to the thickness required, several 7 mm thick plates were welded together by TIG welding. By using this arrangement, test pieces for preliminary experiments were manufactured easily. In those preliminary experiments, the critical parameters were evaluated. In *Appendix 3* the parameters used in the experiments for welding thicker sections by filler wire are shown.

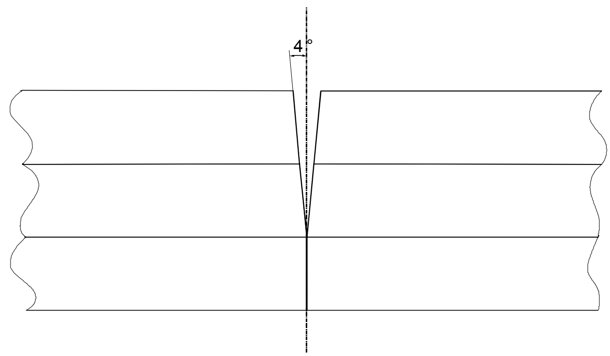


Figure 3.9. An example of the arrangement used in the preliminary welding experiments for thicker sections.

3.4.2 Hybrid welding

First filling pass

Multi pass hybrid experiments for the first filling pass were made with a plate thickness of 20 mm. A partially grooved V joint geometry, with a root face of 4 mm in a butt joint was used, *Fig. 3.7*. The angle of the groove was varied from 8^o to 12^o according to the stage of the experiments. As in the filler wire experiments for the first filling pass, the root weld was welded with a plain laser and filler wire, *Table 3.4*.

In order to receive optimal parameter combination and the combined effect of the parameters, the TAGUCHI test program was used with the orthogonal matrix L9. In that matrix four different factors were varied at three levels. Those four factors were: **wire feed rate** (and due to that, MIG parameters), **focal point position** according to the root weld, **distance D_{LA} and the welding direction** for which only two different values were given, *Table 3.6 and Appendix 4*.

Table 3.6. Factors and their values in the first filling weld TAGUCHI experiment, Appendix 4.

Factor			Levels		
			1	**2**	**3**
A	Wire feed rate, W_R	m/min	40% v_L	50% v_L	60% v_L
B	Focal point position, f	mm	5	7	9
C	Distance D_{LA}	mm	0	1.5	3
D	Torch orientation, D_t	-	Leading	Leading	Trailing

In *Table 3.6* v_L stands for the calculated groove volume, according to which the wire feed rate was calculated by *Equation 2.1*. In that equation, the cross-sectional area of the groove geometry, A_G was calculated for every joint in the experiments by the measured groove geometry after root pass and the focal point position used. The focal point position determined the depth for the calculation and the groove geometry the width of it. Constant parameters used in the TAGUCHI experiments for the first filling passes are shown in *Appendix 4*.

A result of the output received from the TAGUCHI experiments was the filling effect, h_{fill}. It was calculated according to *Fig. 3.10*. That value was attenuated if there was lack of fusion or other defects seen in the cross-sections. Due to the dramatic effect on the weld quality of the lack of fusion between the root weld and first weld it took half of the points off. If there was poor adhesion between the passes, one point was taken off from the measured and calculated filling value. For example if h_1 was measured to be 14 mm and h_2 10 mm, the filling effect h_{fill} was then 4 mm. If there was lack of fusion noticed in the macrograph, the result of the weld in the TAGUCHI calculation was 2 and if poor adhesion was noticed the result was 3.

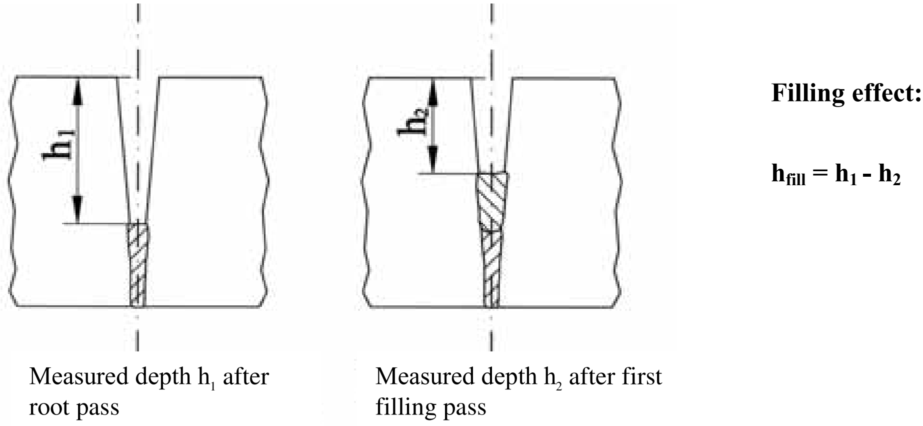
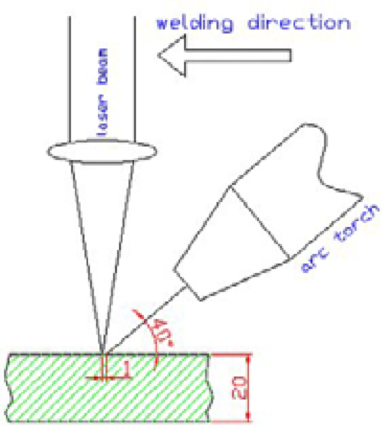


Figure 3.10. Defining the filling effect h_{fill} according to the measurements.

Thicker sections

When welding full 20 mm thick plates, grooves as in the TAGUCHI experiments were used with groove angles of 8 and 10°. The root weld was welded by filler wire laser welding as well as in some testpieces also the first filling pass in order to study the filling effect of the arc in the upper sections. In *Appendix 5*. the variable parameters used in the experiments of 20 mm thick plates are shown as well as the varied parameters. *Fig. 3.11* shows an example of the experimental set-up.



Wire feed rate, W_R	9,7 m/min
Focal point position, f	0 mm
Distance, D_{LA}	1 mm
Torch angle, α_t	40°
Torch orientation, D_t	Trailing
Groove angle,β	10°
Welding speed, V_W	0,5 m/min

Figure 3.11. An example of the set-up used in hybrid experiments for 20 mm thickness.

In addition of 20 mm thick sections, the plates of thickness of 30 mm were welded. Also in those pieces first and even second filling passes were made by the laser with filler wire. The groove geometry was kept constant with a groove angle of 8^o and 10^o. In *Appendix 6* is shown the parameters used in the experiments for thicker sections than 20 mm. The symbols and the explanations are as in *Fig.3.11*. Also the constant parameters were the same.

In order to study the welding of wider grooves, experiment for a plate thickness of 60 mm was made using the parameters received from the previous experiments. The root weld was made with an electron beam with a thickness of 30 mm. So the groove to be filled by hybrid welding was like that shown in *Fig. 3.12*. In which, the set-up of the torch and laser beam can be seen. The parameters are shown in *Table 3.7*.

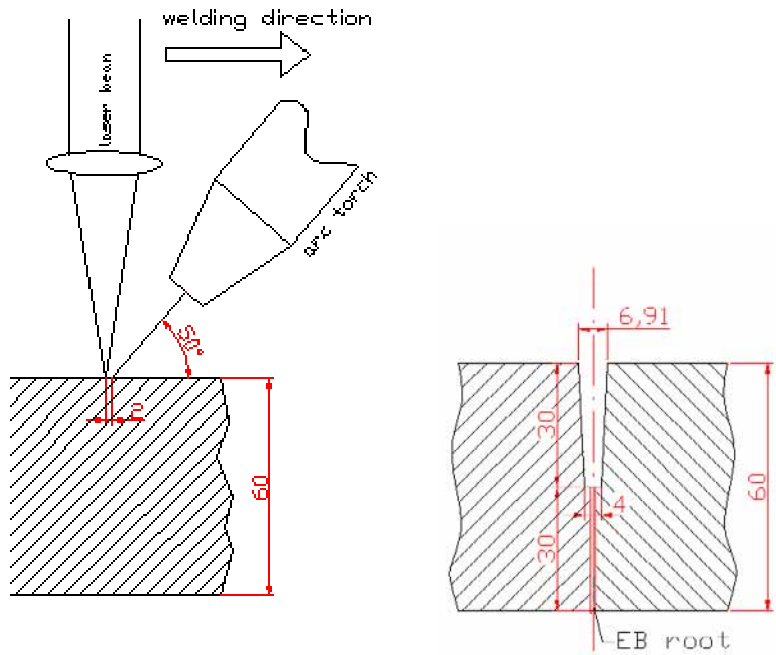


Figure 3.12. The set-up for hybrid welding of 60 mm thickness and also the groove geometry used.

Table 3.7. Variable parameters used in the experiments of 60 mm thick plates in which the EB root was utilized.

Weld	Wire feed rate, W_R [m/min]	Focal point position, f [mm]	MIG		
			Stickout, b [mm]	Voltage, U [V]	Current, I [A]
1.1	13	-24	22	23.3	66
1.2	16	-24	22	24.7	80
1.3	18	-17	22	25.8	96.9
1.4	18	-11	22	25.8	120
1.5	18	-8	16	25.9	134
1.6	18	-3	16	26	116
1.7	18	0	16	26	126

3.5 Analyzing

In order to determine the suitability of the processes for multi pass welding in narrow groove, the evaluation of the welds was made by macrographs of cross-sections of the welds. Some of the testpieces were also radiographed. Since the main point of this thesis was the welding procedure and to the well known fact that in austenitic stainless steel welds the mechanical properties of the joint are not usually critical, no major attention was laid on microstructure of the welds. During the welding, the process stability was carefully detected by the author. Measurements, in which for example the filling effect h_{fill}, was determined, were made from cross-sections of the weld and also from macrographs.

4. Results

4.1 Single pass experiments

4.1.1 Laser welding with filler wire

Single pass experiments were made using the TAGUCHI test program. This procedure gives the optimal parameter combination, and also the effect of the individual parameters to the process. For the results of the single pass experiments were chosen the **penetration effectiveness** (P_E) with welding speed of 0,5 m/min and the **maximum welding speed** (V_{WMAX}) with the full penetration. The penetration effectiveness was determined by multiplying the penetration by the welding speed. *Table 4.1* shows the results of the individual welds.

Table 4.1. Results of TAGUCHI experiments for the single pass filler wire welds.

Weldnr	P_E [mm^2/min]	V_{WMAX} [m/min]
1	3500	0.5
2	3343.3	0.5
3	3099	0.3
4	3500	0.5
5	2511	0.3
6	3400	0.5
7	2085.2	0.3
8	3336.3	0.6
9	2519.9	0.3

According to the results in *Table 4.1*, the optimal parameter combination can be calculated according to the TAGUCHI test program, *Table 4.2*, as well as the effect of variable parameters on the process.

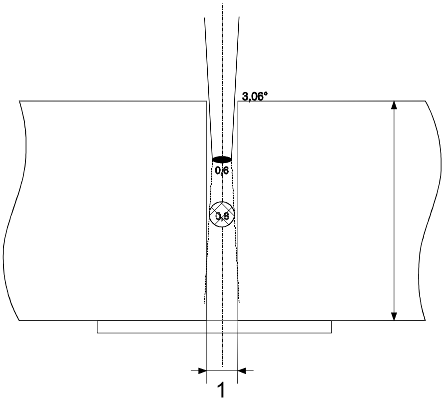
Table 4.2. Calculation routine of the TAGUCHI experiment for the first filling pass (Karjalainen, 1990).

Parameter		P_E [mm^2/min]	V_{WMAX} [m/min]
A	Wire feed rate, W_R [m/min]	A1 (-10%) = **3314.1** A2 (0%) = 3137 A3 (+10%) = 2647.13	A1 (-10%) = **0.433** A2 (0%) = **0.433** A3 (+10%) = 0.4
B	Wire feed angle, α_W [^{o}]	B1 (20) = 3028.4 B2 (40) = **3064** B3 (60) = 3006.3	B1 (20) = 0.433 B2 (40) = **0.466** B3 (60) = 0.366
C	Focal point position, f [mm]	C1 (-2) = **3412.1** C2 (0) = 3121 C3 (2) = 2565.1	C1 (-2) = **0.533** C2 (0) = 0.366 C3 (2) = 0.366
D	Interaction point of the wire, W_Z [mm]	D1 (-2) = 2843.6 D2 (0) = 2942.8 D3 (2) = **3311.8**	D1 (-2) = 0.366 D2 (0) = 0.366 D3 (2) = **0.466**

The optimal parameter combination, calculated by the TAGUCHI test program with two different results, is almost congruent. The only difference was with the wire feed rate, which received two different values (e.g. -10% and 0% subtracted from the groove volume) in the case of the maximum welding speed with full penetration. The value for the result of penetration effectiveness was -10% from the groove volume. The optimal parameter combination can be then summarized:

Wire feed rate, W_R	-10/0% subtracted from the groove volume, V_L
Wire feed angle, α_W	40^o
Focal point position, f	2 mm below the surface of the plate
Interaction point, W_Z	2 mm below the focal position.

Fig. 4.1. Shows the optimal set-up and additionally the weld made with the optimal parameter combination.



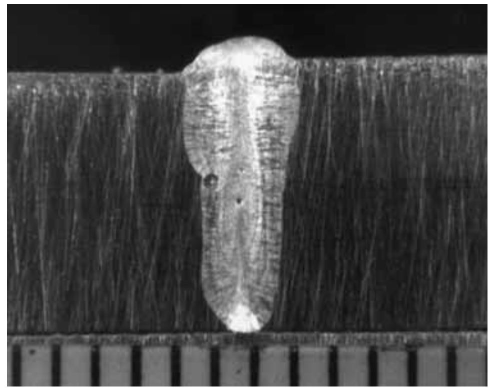


Figure 4.1. The setup and cross-section of the weld made by optimal parameter combination received from the single pass TAGUCHI experiments with filler wire, weld OPTI 1. In Appendix 1.

The differences in the effectiveness of the individual parameter can be clearly seen, when the different results were used in the calculation routine, *Fig. 4.2*. When the result was penetration effectiveness, the most important factor on the process was the focal point position with a value of 25%. Quite close to that, was the wire feed rate (20%). The lower values were received for the interaction point of the wire and the wire feed angle, 14% and 1.9% respectively. In the case, in which the maximum welding speed was used as a result for the calculation, again the focal point position was the most important one, but with a value of 31%. The next factors were the interaction point of the wire and the wire feed angle, with 21%. The lowest value was calculated for the wire feed rate (7.6%).

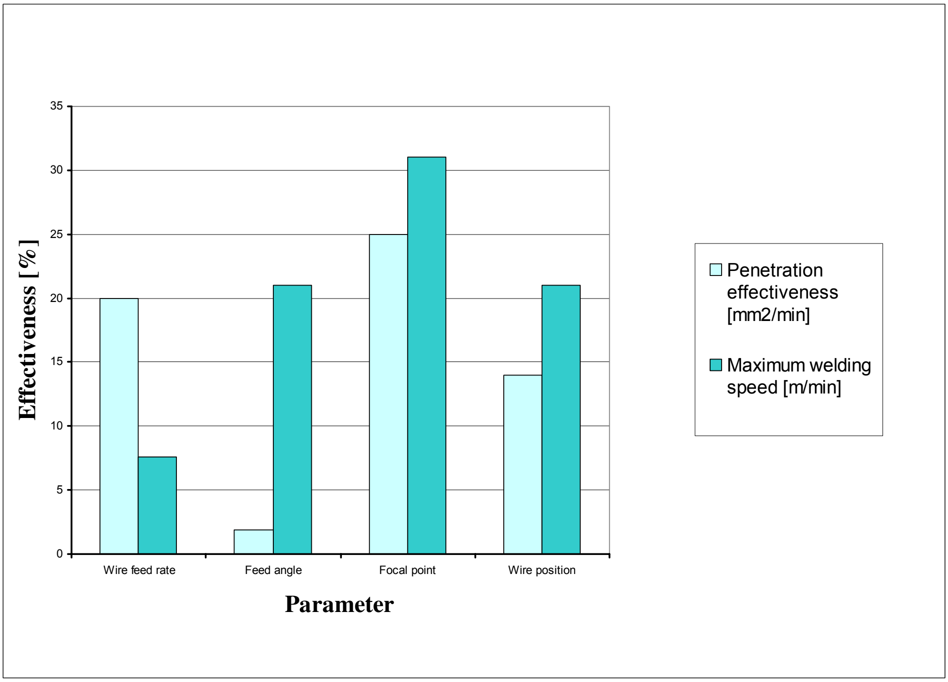


Figure 4.2. The effectiveness of the parameters changed in the TAGUCHI experiment for the single pass welds with filler wire.

4.1.2 Hybrid welding

The single pass hybrid welding experiments were made with a plate thickness of 6.5–6.9 mm, with a 1 mm air gap at the butt joint. The experiments were made to study the primary parameters of the process, and the effect of the MIG arc. The experiments were made with the set-up shown in *Fig. 4.3*. Both torch orientations were used (e.g. leading and trailing edge), *Figs. 4.3 and 4.4.*

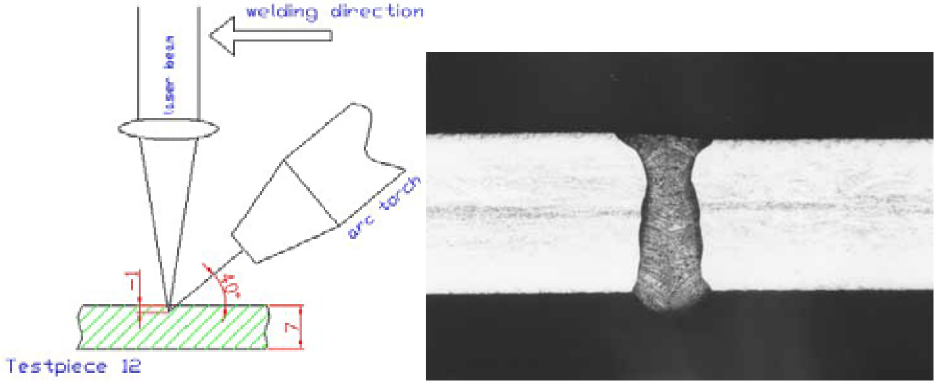


Figure 4.3. The set-up and cross-section of the hybrid weld with a thickness of 6.5 mm. Other parameters: Laser power 3 kW, air gap 1 mm, welding speed 0.7 m/min and filler wire feed rate 9.7 m/min.

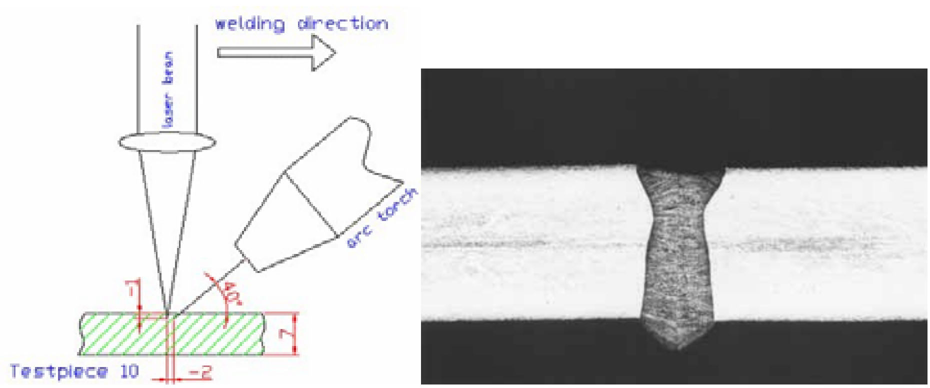


Figure 4.4 The set-up and cross-section of the hybrid weld with a thickness of 6.7 mm. Other parameters: Laser power 3 kW, air gap 1 mm, welding speed 0.7 m/min and filler wire feed 9.7 m/min.

Due to the good gap bridging ability and excessive penetration, the welding speed was raised in the experiment up to 0.9 m/min, *Fig.4.5* and *Fig. 4.6*.

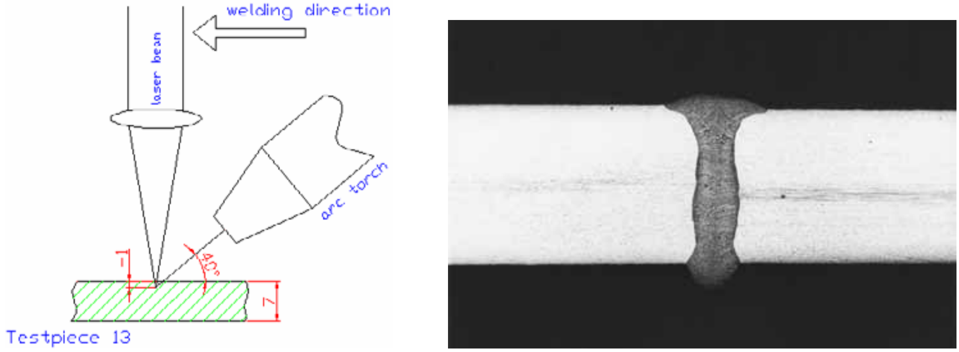


Figure 4.5. The set-up and cross-section of the hybrid weld with a thickness of 6.7 mm. Other parameters: Laser power 3 kW, air gap 1 mm, welding speed 0.9 m/min and filler wire feed 12.5 m/min.

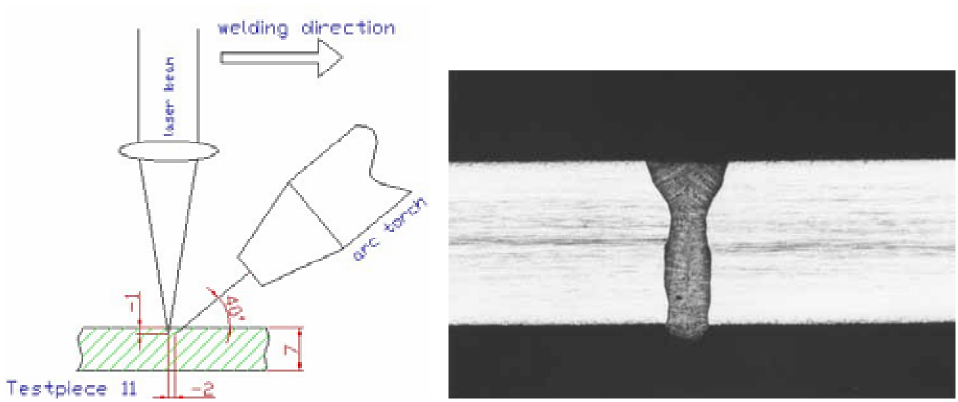


Figure 4.6. The set-up and cross-section of the hybrid weld with a thickness of 6.8 mm. Other parameters: Laser power 3 kW, air gap 1 mm, welding speed 0.9 m/min and filler wire feed 12.5 m/min.

Table 4.3 shows the widths of the single pass hybrid welds. The widths have been measured on three points from the cross-sections: 1 mm from the surface, middle and 1 mm from the lower surface. In *Table 4.3* the calculated width/depth -ratio from the average value of the width divided by penetration is shown.

Table 4.3. The widths of the single pass hybrid welds and width/depth -ratio.

Width [mm]	Figure 4.3	Figure 4.4	Figure 4.5	Figure 4.6
Bead	2.5	3.2	2.2	2.8
Middle	2.5	2.8	2.0	2.0
Root	2.8	3.2	1.6	1.7
Average	2.6	3.1	1.9	2.17
Width/depth	0.43	0.52	0.32	0.36

4.2 Multi pass experiments

4.2.1 Laser welding with filler wire

4.2.1.1 Root pass

In the beginning of the multi pass experiments, the main attention was laid on the root weld. The groove angles tested were selected to be as small as possible, according to the accessibility of the laser beam down to the root of the joint. It was possible to make the root weld without weld defects with groove angles of 8^o and 10^o. A small air gap (up to 1 mm) between the plates to be welded ensured the penetration through the whole material thickness and also the quality of the weld. *Table 3.4* shows the good parameter combination for the root weld when the whole thickness of the testpiece is 20 mm and the joint is a partially grooved V with a 4 mm parallel root face, *Fig. 4.7*.

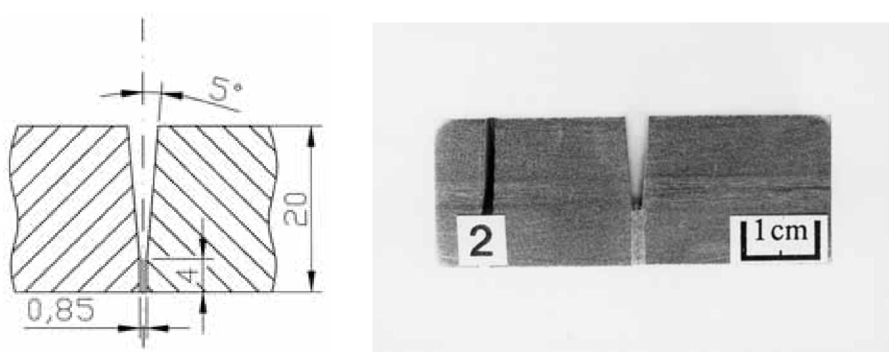


Figure 4.7. The groove geometry and the root weld with acceptable quality. Parameters in Table 3.4.

4.2.1.2 First filling pass

The experiments for the welding of the first filling pass with the filler wire were done using testpieces with the root pass welded first, *Fig. 4.7*. The main interest of the experiments was to find parameters, by which the weld effectively filled the joint without weld defects for example shown in *Fig 4.8*.

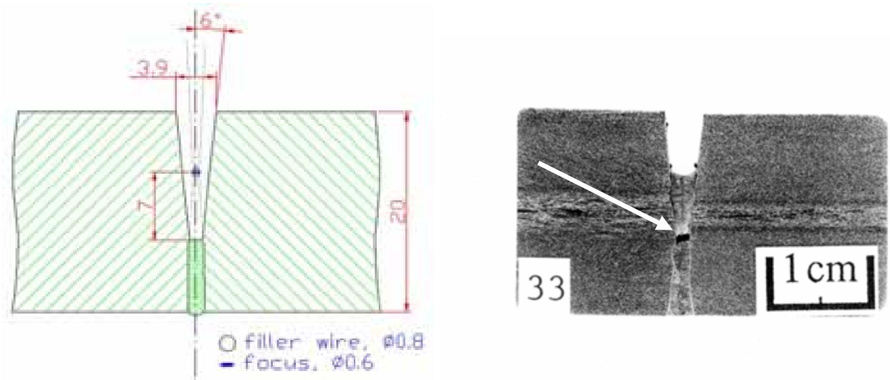


Figure 4.8. The set-up and cross-section of the first filling weld, testpiece 3.3. Parameters in Appendix 2. A lack of fusion is clearly seen between the passes.

In the beginning of the experiments it was noticed that not only the amount of filler wire fed to the process had an affect on the penetration and the quality of the weld, butthe main thing is concerning the interaction between the filler wire and laser beam, of course together with the groove configuration. If an excessive amount of filler wire is fed to the joint, the laser does not have the power to melt the wire and groove surfaces properly and weld defects like lack of fusion will occur, *Fig. 4.8*. The filler wire feed rate can be at a maximum level if the interaction point of the laser and wire is properly selected. Naturally at the focal point the melting capability of the laser is at its maximum. But according to the small size of the focal point (diameter of 0.6 mm) and according to the diameter of the filler wire, the more reliable way is to adjust the wire for example 2 mm below the focal point without loosing the melting power dramatically, *Fig. 4.9*. Acceptable results are also achieved when the wire is pointed deeper than 2 mm below the focal point but then melting is not so effective, *Fig. 4.10*. A very critical thing in pointing the wire to the melt is that no good results are achieved when the wire is adjusted over the focal point. This will affect strongly on the balance of the process and weld defects will occur together with poor penetration.

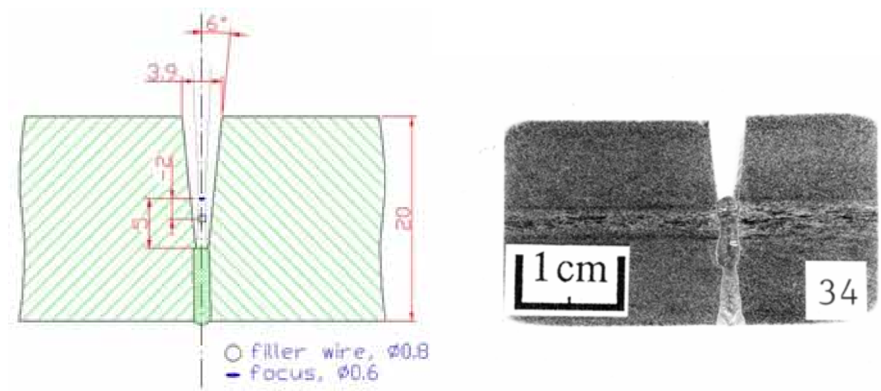


Figure 4.9. The set-up and cross-section of the first filling weld, testpiece 3.4. Parameters in Appendix 2.

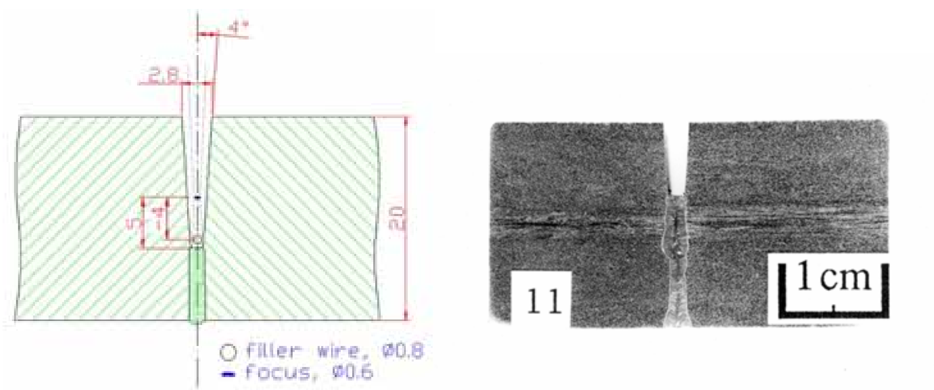


Figure 4.10. The set-up and cross-section of the first filling weld, testpiece 1.1. Parameters in Appendix 2.

According to the requirement of the minimum number of the passes needed to fill the whole thickness, the angle of the groove should be as narrow as possible. But because of the focusing of the laser beam, the groove angle should be wider than the focusing angle. Another limiting factor is the amount of distortion. Owing to the joint configuration, angular distortions will occur by bending the plates towards the welding side. This will make the groove narrower after every pass. There is a need for the laser beam to reach the bottom of the joint together with the filler wire. That is why the groove angle should be a few degrees wider than the focusing angle. In the experiments, with a focusing angle of 6.12^o and with a plate thickness of 20 mm, a groove angle of 10^o was found to be the most suitable, *Fig. 4.11*, although good results were also achieved with an angle of 8^o, *Fig. 4.10*.

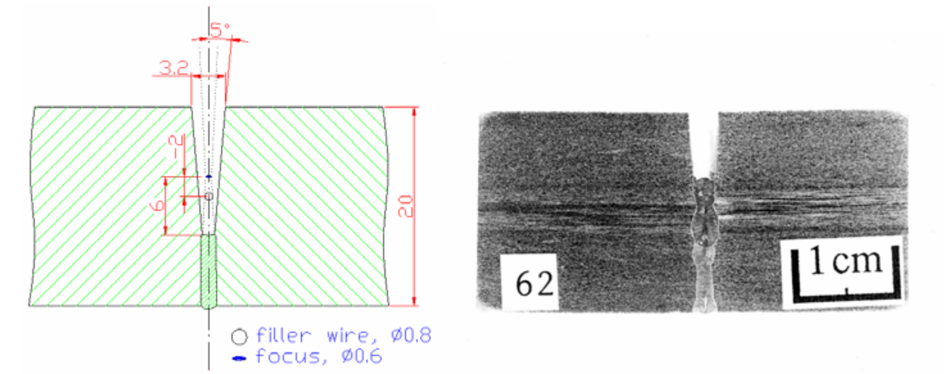


Figure 4.11. The set-up and cross-section of the first filling weld, testpiece 6.2. Parameters in Appendix 2.

When the above-mentioned filler wire feed rate and the interaction point of the laser beam and filler wire were optimized, good results were also achieved with a groove angle of 8^o, *Fig. 4.10*. However, when the amount of the filler wire fed increased and was pointed towards the focal point, the results collapse, *Fig. 4.12*. Also the groove angles of 12^o were explored, *Fig. 4.13*. Although good and reliable results were achieved, still the filling of the passes was not as efficient as with the narrower grooves.

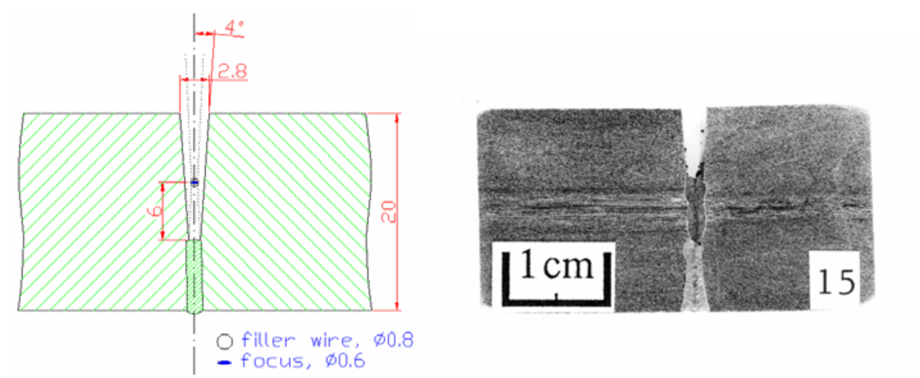


Figure 4.12. The set-up and cross-section of the first filling weld, testpiece 1.5. Parameters in Appendix 2.

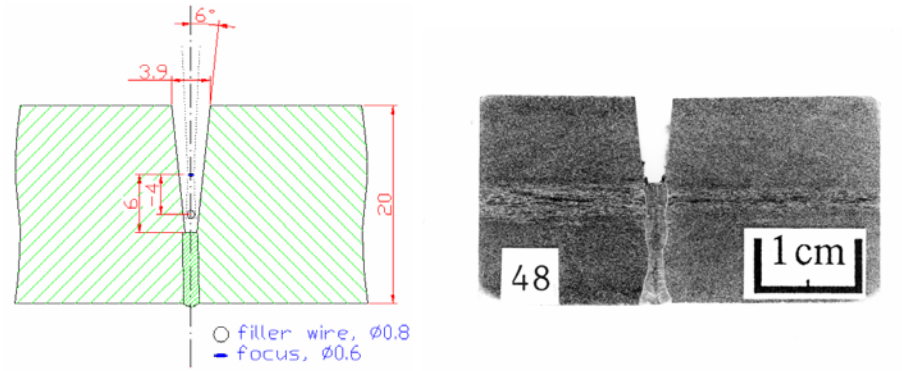


Figure 4.13. The set-up and cross-section of the first filling weld, testpiece 4.8. Parameters in Appendix 2.

The focal point position was adjusted according to the previous weld bead. Before the experiments it was assumed that the higher the raise in the focal point, the deeper the filling pass. This was also noticed during the experiments. It was also pointed out, that because the amount of filler wire needed was calculated according to the joint cross-section to be filled, the amount of wire increased to an excessive range such that it could not be melted properly by the laser power used, *Fig. 4.14*. The best results were achieved, when the focal point was raised 5 or 6 mm from the surface of the root pass, *Figs. 4.10 and 4.11*.

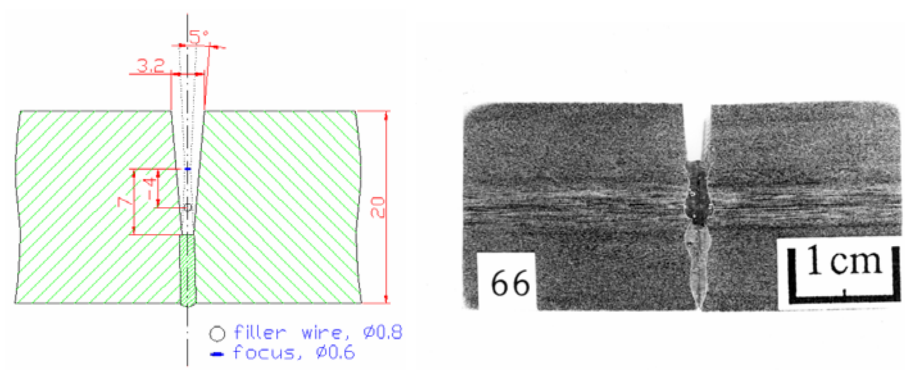


Figure 4.14. The set-up and cross-section of the first filling weld, testpiece 6.6. Parameters in Appendix 2.

Owing to the filling of the groove dominating the efficiency of the process, the filling of the first pass in the experiments is shown in *Table 4.4*. In the same table the quality of the weld is described.

Table 4.4. The filling of the first pass in the experiments and quality description.

WELD	Filling [mm]	Quality description
1.1	6.21	OK
6.2	6.03	OK
3.3	7.43	Lack of fusion
3.4	5.79	OK
1.5	6.08	Poor adhesion
6.6	7.42	Lack of fusion
5.7	4.55	OK
4.8	5.22	OK
2.9	5.43	Poor adhesion

4.2.1.3 Filling passes for thicker sections

The number of the passes was increased above the first filling pass in the welding experiments of thicker sections. Previous knowledge of the process was used in the experiments. Filler wire experiments were made up to a thickness of 35 mm using a partially grooved V -joint with a groove angle of 8^o and 10^o and with a parallel root face of 4 mm. Accessibility of the laser beam to the joint was secured with the experiments of the root pass and first filling pass, so the main attention in the experiments for the thicker sections was to find the effective filling of the groove and stability of the process, i.e. acceptable quality of the weld produced.

Fig. 4.15 shows the cross-section of the weld, in which a total of three passes, were welded. The welds filled totally 15 mm, from which the last weld filled 4.5 mm. Every weld had an adequate adhesion to the previous weld and also the groove surfaces were properly melted. These indicated the applicability of the parameters used in welding. The main parameters in a successful process were found to be the amount of filler wire fed and the interaction point of the filler wire and the laser beam. Adjustment of the laser beam together with the filler wire according to the groove was also found to be important for a stable process.

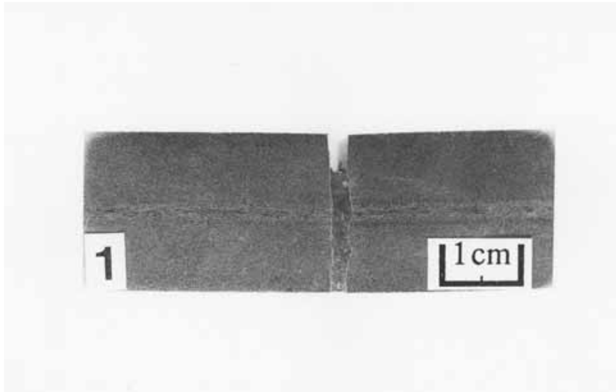


Figure 4.15. The cross-section of the weld in a 20 mm thick tespiece. Parameters in Appendix 2.

Fig. 4.16 shows the cross-sections of the welds with a total thickness of 20 mm. Although in the upper section of the groove, the amount of filler wire fed to the process in the experiments was up to 8 m/min, still more reliable results were achieved when the rate was from 4.5 up to 6 m/min. Decreasing the filler wire feed rate decreased the filling of the individual pass respectively, but melting of the surface of the previous pass and the groove surfaces was assured. Decreased filling means more passes to be welded, *Fig. 4.16*.

Figure 4.16. Cross-sections of the welds with a plate thickness of 20 mm. On the left hand testpiece 2. with 5 passes and on the right hand testpiece 3. with six passes. Parameters in Appendix 2.

As it was reported in section 4.2.1.2, the interaction point of the filler wire and the laser beam was an important factor for a stable process. The best results according to the filling and quality of the pass were found when the wire was pointed below the focal point position. No great difference was found if the interaction point changed from 2 up to 4 mm below the focal point, *Figs. 4.16 and 4.17*.

Figure 4.17. The cross-section of the weld with a plate thickness of 35 mm. Testpiece 2 with 8 passes. Parameters in Appendix 3.

The limiting factor in the thickness of the plate to be welded was found to be the growing air gap. The defect resulted from crossing the limit was lack of fusion on the groove surface and is shown in *Fig. 4.18*. The limit for the air gap was found to be about 2.8 mm. This means thicknesses from 18 to 21 mm with a groove angle of 10^{o}, depending on air gap used between the root faces. With a groove angle of 8^{o} the same thicknesses are from 21 to 24 mm.

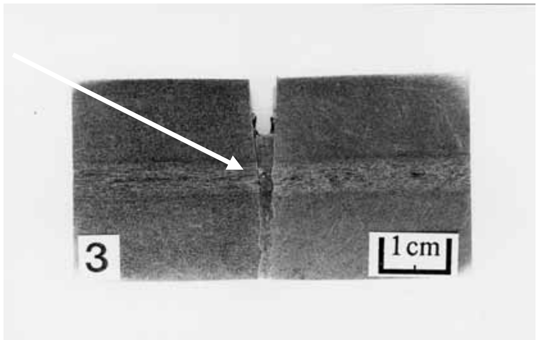


Figure 4.18. The cross-section of the weld with a plate thickness of 30 mm. Testpiece 3. The lack of fusion in the pointed area. Parameters in Appendix 3.

In the multi pass welds, some weld defects like pores and lack of fusion were noticed. Lack of fusion comes from the unstable process or unsuitable conditions, i.e. excessive air gap as resulted earlier. More pronounced was the existence of pores, *Fig. 4.19*. Liquid metal behind the keyhole solidified very rapidly. This hindered the bubbles, which were moving upward, before they were able to leave the molten metal. Owing to the welds being partially penetrated, rapid changes in the root of the keyhole trapped bubbles into the solidified weld. Owing to the insufficient shielding of the molten metal in the narrow groove, the fine oxidized metal dust was noticed in the surface of the welds. This dust had an affect on the pore formation but not critically.

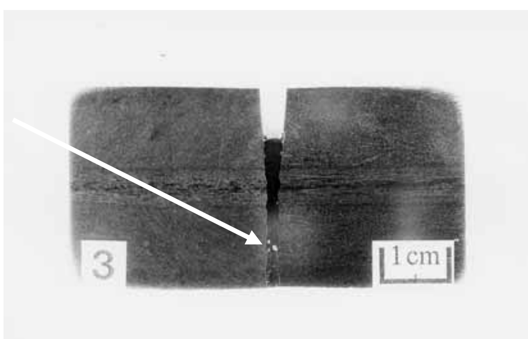


Figure 4.19. The cross-section of the weld with a plate thickness of 30 mm. Testpiece 3. Pores in the pointed area. Parameters in Appendix 3.

4.2.2 Hybrid welding

The multi pass hybrid experiments were started using the TAGUCHI test program in order to study the effect of the parameters and the optimal combination for the first filling pass. The root pass for the test pieces was welded by the laser with filler wire to secure the quality and also because of the good results received from the filler wire experiments, *Fig. 4.7*. Additionally in some testpieces for thicker sections the first, second and even third filling passes were made by laser welding with filler wire. Still in general, when the more upper section of the groove was welded, the more common process was hybrid welding.

4.2.2.1 The TAGUCHI experiment for the first filling pass

According to the nature of the TAGUCHI test program, the results have to be qualified, and after that the calculation routine gives the optimum parameter combination and the effectiveness of the individual parameter changed. For the results of the experiments, the filling effect, h_{FILL} and the quality of the welds were defined, *Fig. 3.10*. The quality of the welds means the adhesion between the root and the first filling pass. According to the results selected, points were given to the individual welds; filling effect in mm gave the same amount of points, poor adhesion to the root weld took one point off and the lack of fusion between the passes took half of the points off due to the dramatic effect of it on the quality of the weld, see section 3.4.2. *Table 4.5* shows the points of the individual 9 welds.

Table 4.5. The points of the individual hybrid welds in the TAGUCHI experiment for the first filling pass. Cross-sections are shown in Appendix 2.

Nro	Filling effect h_{fill} [mm]	Visual inspection	Points achieved
1	2.6	-	**2.6**
2	4	-	**4**
3	6	Poor adhesion	6 - 1 = **5**
4	4.4	-	**4.4**
5	5.3	-	**5.3**
6	4	Lack of fusion	4 / 2 = **2**
7	3.1	-	**3.1**
8	6	Lack of fusion	6 / 2 = **3**
9	7.7	Lack of fusion	7.7 / 2 = **3.85**

In *Table 4.6* the calculation routine of the TAGUCHI experiment has been made. According to the nature of the routine, the best value for each individual parameter changed can be determined.

Table 4.6. The calculation routine of the TAGUCHI experiment for the first filling pass.

Parameter		Calculation	Best result
A	Wire feed rate, W_R [m/min]	A1= 1/3· (2.6+4+5) p = 3.87 p **A2**= 1/3· (4.4+5.3+2) p = **3.90 p** A3= 1/3· (3.1+3+3.85) p = 3.32 p	**A2 ⇒ 50%V_L**
B	Focal point position, f [mm]	B1= 1/3· (2.6+4.4+3.1) p = 3.37 p **B2**= 1/3· (4+5.3+3) p = **4.10 p** B3= 1/3· (5+2+3.85) p = 3.62 p	**B2 ⇒ 7 mm**
C	Distance D_{LA} [mm]	C1= 1/3· (2.6+2+3) p = 2.53 p C2= 1/3· (4+4.4+3.85) p = 4.08 p **C3**= 1/3· (5+5.3+3.1) p = **4.47 p**	**C3 ⇒ 3 mm**
D	Torch orientation, D_t [leading / trailing]	D1= 1/3· (2.6+5.3+3.85) p = 3.92 p D2= 1/3· (4+2+3.1) p = 3.03 p **D3**= 1/3· (5+4.4+3) p = **4.13 p**	**D3 ⇒ Trailing**

According to *Table 4.6* the best parameter combination is:

Wire feed rate, W_R	5% calculated using *Equation 2.1*
Focal point position, f	7 mm up from the previous pass
Distance, D_{LA}	mm
Torch orientation, D_t	Trailing edge arc torch

The set-up of the parameters can be seen in *Fig. 4.20*. Additionally the cross-section of the weld made by the optimal parameter combination can be seen. According to observations made during the experiments, the trailing edge adjustment of the arc was more sensitive to disturbances in the process, leading to weld defects or incomplete adhesion between the passes, *Fig. 4.20*. Due to this, the same parameter combination was used with the leading edge adjustment, *Fig. 4.21*.

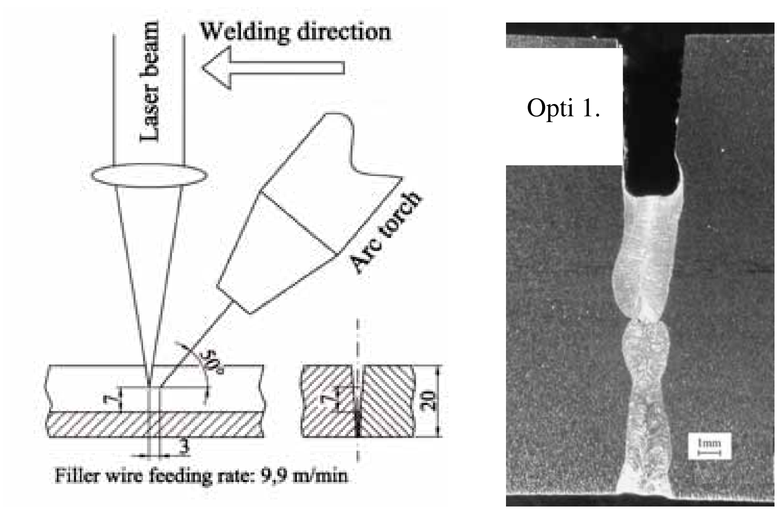
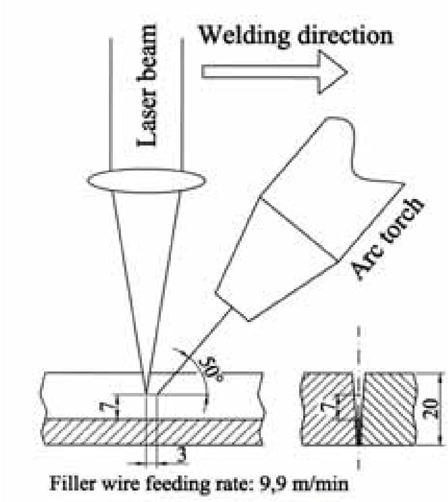


Figure 4.20. The set-up condition and cross-section of the weld made by using the optimal parameter combination from TAGUCHI experiments. Parameters in Appendix 4.



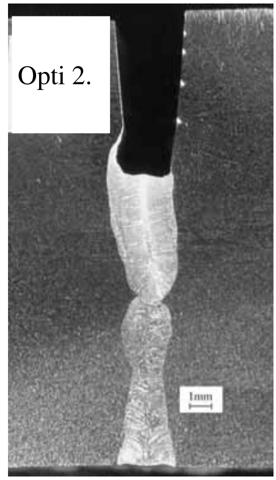


Figure 4.21. The set-up condition and cross-section of the first filling weld made with hybrid weld. Parameters in Appendix 4.

Due to the TAGUCHI calculation routine the effectiveness of the parameters changed can also be calculated from the results achieved. According to these, the most important factor, for the filling effect and also for the quality of the weld, was the distance D_{LA} between the arc and the laser impingement point, *Fig. 4.22*. The second factor was the torch orientation and less effect on the filling and the weld quality was due to the focal point positioning and the wire feed rate.

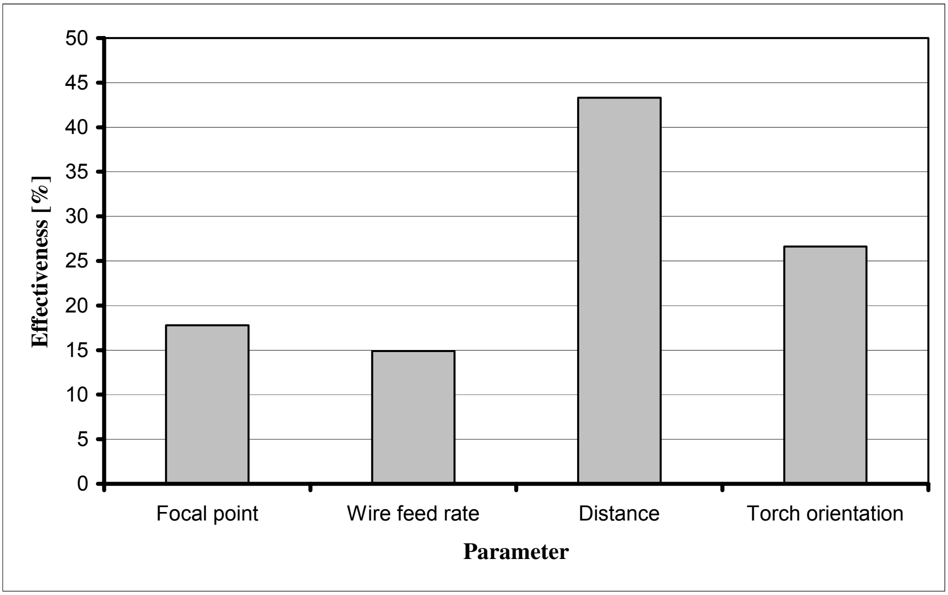


Figure 4.22. The effectiveness of the parameters changed in the TAGUCHI experiment for the first filling pass.

4.2.2.2 Filling passes for thicker sections

The experiments for filling passes were started with a plate thickness of 20 mm. *Fig. 4.23* shows the weld for which the best parameter combination determined from the TAGUCHI experiment was used for the first filling pass and full filling was made for the other two passes. Incomplete adhesion between the root pass and the first filling pass can be clearly seen from the cross-section. The adhesion between the other passes is acceptable. In the upper region of the groove, a minor lack of fusion can be seen. The shape of the first filling pass shows, that welding has occurred by the keyhole mechanism. This is also the mechanism for the other filling passes, but it is not so clearly visible because of the excessive filler wire feed rate, which raised the heat input of the arc. This can be seen from the wider weld than in the previous ones. One reason for this is also the decrease in welding speed from 0.7 to 0.5 m/min. Also the adjustment of the arc is not at the optimum, which can be seen from the asymmetric weld profile.

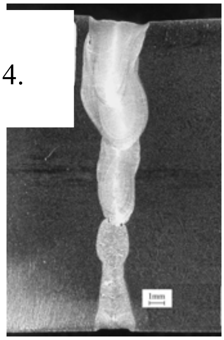


Figure 4.23. The cross-section of the weld in testpiece 4. Parameters in Appendix 5.

Fig. 4.24 shows the weld with a better geometry for the individual welds. The welds follow the opening of the groove and no excessive amount of base material has been melted. It is clearly seen that welding has occurred by the keyhole mechanism. For example, the width/depth ratio of the first filling pass is 0.39. The adhesion, at the most critical point, i.e. between the root pass and the first filling pass, is also better. Still overlapping between these passes should be more than 0.7 mm measured from the testpiece. Overlapping between the first and second filling pass (1.8 mm) ensures better adhesion. From the point of view of total heat input, the overlapping between the third and last filling pass (3.8 mm) is too much.

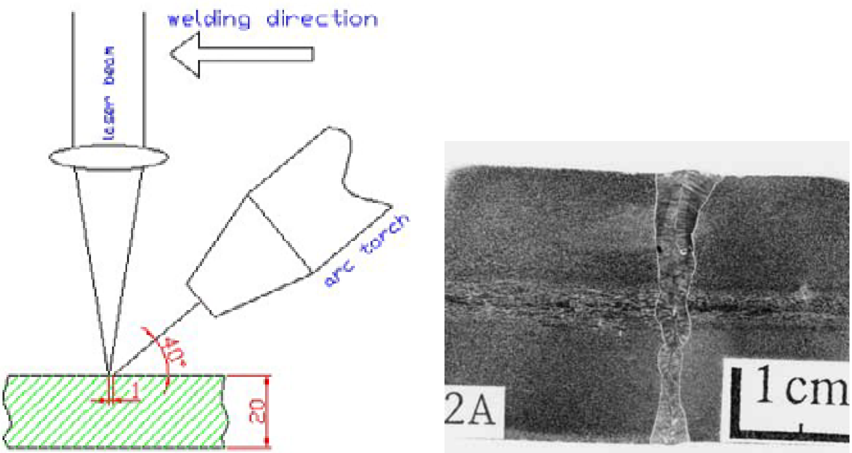


Figure 4.24. The set-up condition and the cross-section of the weld with a thickness of 20 mm filled with 4 passes, testpiece 2A. Parameters in Appendix 5.

The critical defects in the adhesion between the passes are shown in *Fig 4.25*. Although the first filling pass has been made by laser welding with filler wire, still the penetration of the weld is incomplete, and thus adhesion has become poor to the root weld. Also the penetration of the first hybrid pass has not been deep enough to make a sound adhesion. The second and the last hybrid passes have penetrated through the pass made earlier, so the parameters and adjustments have been improper for the welding task. Also comparison to the weld in *Fig. 4.24*, which has been made with the same parameters, illustrates that the reason for poor adhesion has to be due to the groove geometry, which was narrower (i.e. 8^o), than in the previous welds.

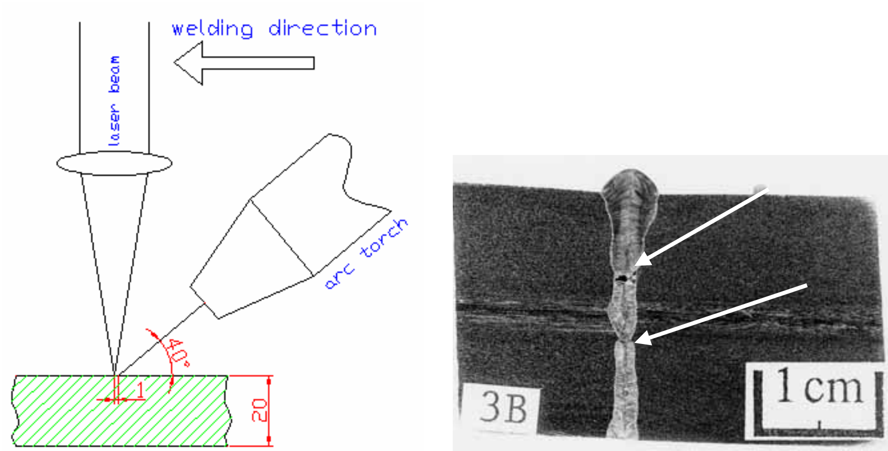


Figure 4.25. The set-up condition and the cross-section of the weld with a thickness of 20 mm, testpiece 3B. The defects are pointed out with arrows. Parameters in Appendix 5.

Fig. 4.26 shows the filling of the individual passes in different welds, when welding 20 mm thick plates. The first pass is the root pass and next two passes are the filling passes. The 20 mm thick plates were welded mainly with four passes. Owing to the groove opening, the filling decrease towards the surface. The root pass, which was made by filler wire, had an average filling of 7 mm. For the first and second filling passes it was about 6 and 5 mm, respectively. This means, that for the fourth filling pass only about a 2 mm groove depth was to filled up. Although, the wire feed rate was increased, still the need for four passes was evident in order to produce acceptable welds. This can be seen from the filling of testpiece B2, *Fig. 4.23*. The fourth passes penetrated strongly on the former ones, and thus filling of these was difficult to define. So they are not plotted in *Fig. 4.26*.

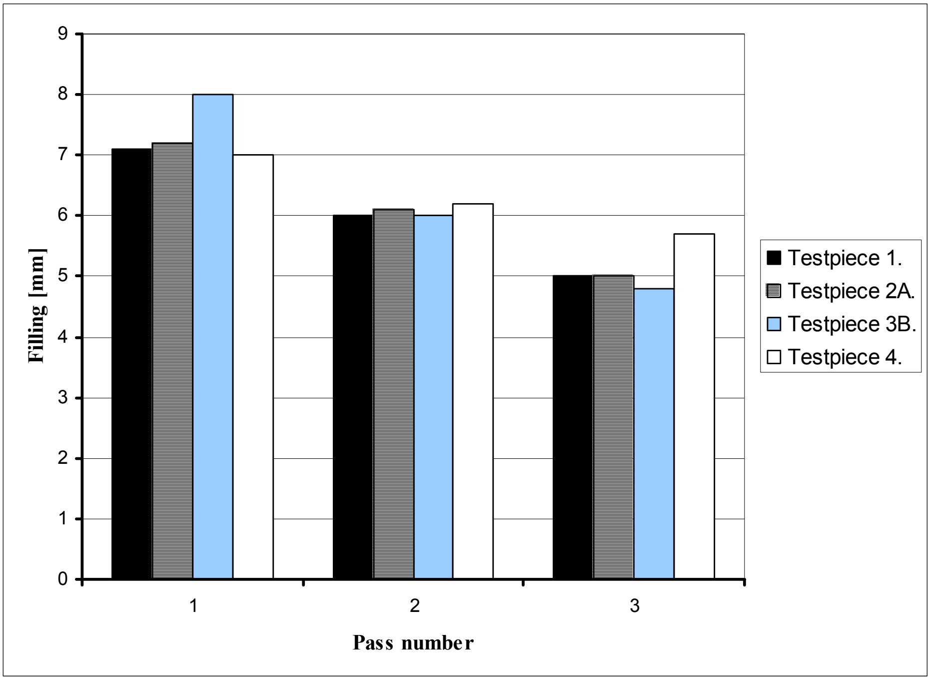


Figure 4.26. The filling of the individual passes in different testpieces of a 20 mm thick plate. The testpieces refer to the Appendix 5.

In the welding of 30 mm thick plates, the same kind of groove geometry was used as in the welding of 20 mm plates: a partially grooved V with a parallel root face of 4 mm. The groove angles used were 8^{o} and 10^{o} and the root and at least the first filling pass were welded by the laser with filler wire without an arc. *Fig. 4.27* shows the weld, in which the root and first filling pass were welded with plain filler wire. The groove was filled with four hybrid passes and the torch orientation was leading according to the laser beam. As can be seen the adhesion between the passes was acceptable in every case. This can also be seen in *Table 4.7*. The welds follow nicely the geometry of the groove, and are narrow as possible in order to join the joint surfaces. For the last pass, which was the widest one, the width/depth -ratio was 0.55, which indicate clearly keyhole welding.

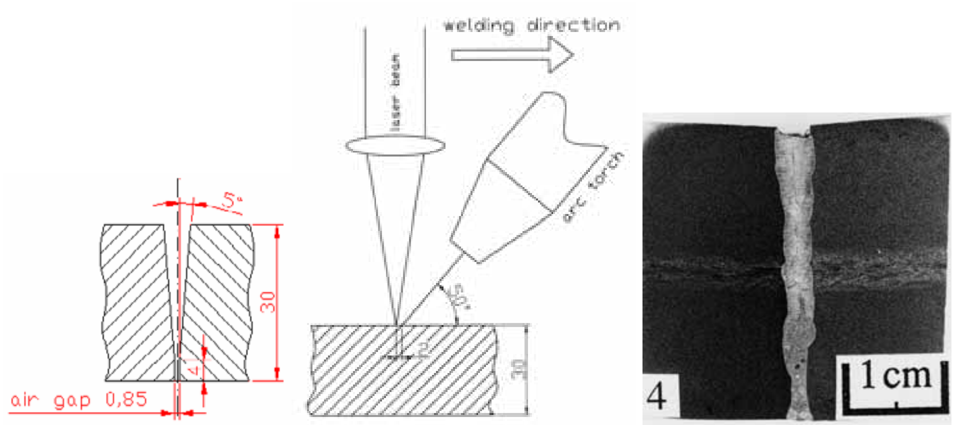


Figure 4.27. The groove geometry, the set-up condition and cross-section of the weld with a thickness of 30 mm, testpiece 4. Parameters in Appendix 6.

Fig. 4.28 shows the testpiece, in which a 30 mm thick section with the same kind of groove geometry as in *Fig. 4.27*. The first three passes were made with a laser and filler wire and the three latter ones with the hybrid welding.

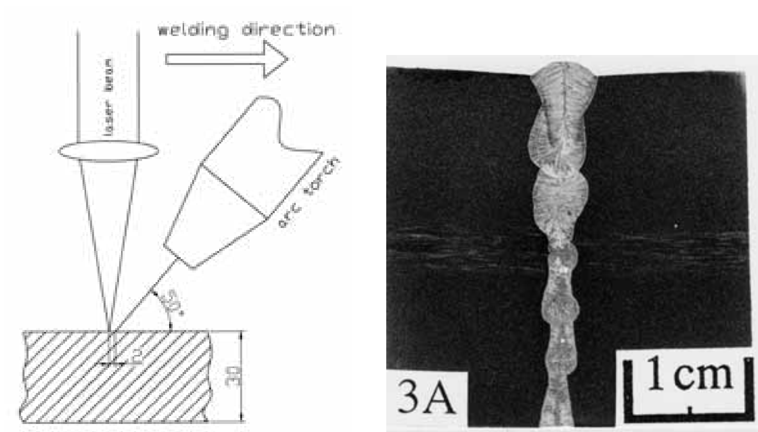


Figure 4.28. The set-up condition and cross-section of the weld with a thickness of 30 mm, testpiece 3A. Parameters in Appendix 6.

When comparing *Figs. 4.27* and *4.28* it can be seen the effect of the filler wire feed rate and due to that the arc parameters. In the testpiece shown in *Fig. 4.28*, the amount of filler wire was in the last three filling passes 12, 15 and 10 m/min.

In the testpiece shown in *Fig. 4.27* it was 8, 8 and 12 m/min, respectively. The differences between the geometries of the passes are clear: they are much wider in the testpiece in 3A than in 4, *Fig. 4.29*.

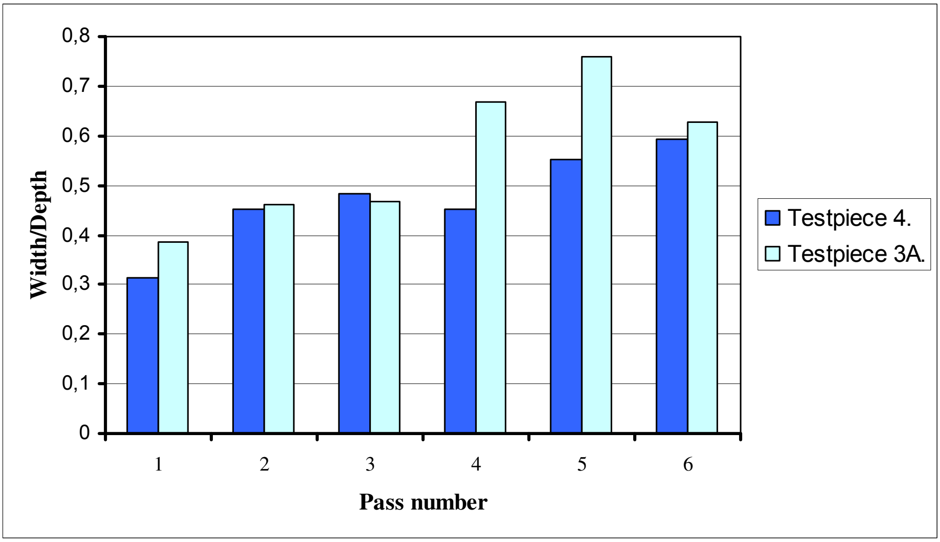


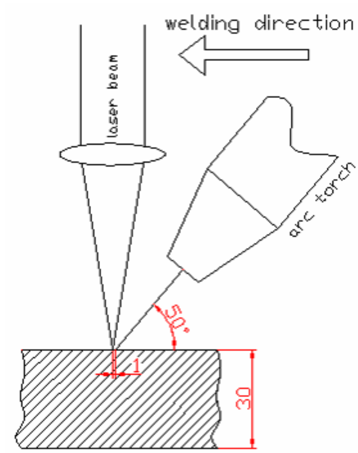
Figure 4.29. The width/depth ratio of the individual six passes in the testpieces 3A and 4.

Table 4.7 shows the overlapping of the passes to the previous one for the welds in testpieces 3A and 4. The overlapping is decreasing when increasing the filler wire feed. This means that the penetration decreases with increasing the filler wire feed although at the same time the arc voltage and current are increasing.

Table 4.7. The overlapping of the passes to the previous one.

Area	**Overlapping [mm]**	
	Weld 4	**Weld 3A**
Fifth / Sixth	4,5	4,0
Fourth / Fifth	2,0	1,1
Third / Fourth	2,2	0,64
Second / Third	2,6	2,1
First / Second	1,0	1,1

Fig. 4.28 shows the weld, in which the hybrid passes have been welded by the leading edge torch orientation. *Fig. 4.30* shows the same kind of weld, in which the only difference is that the three upper hybrid passes were welded by the trailing edge arc torch orientation. A defect by the form of lack of fusion can be clearly seen. This shows that the trailing edge orientation is more sensitive to defects than the leading edge orientation. This and an unstable process with the trailing edge orientation was noticed also visually during the welding experiments.



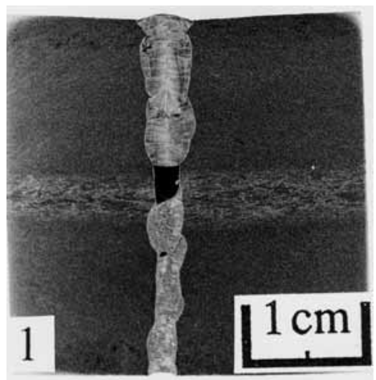


Figure 4.30. The set-up condition and cross-section of the weld with a thickness of 30 mm, testpiece 1. Parameters in Appendix 6.

Another example of the effect of the torch orientation is shown in *Fig. 4.31*. In that testpiece the amount of filler wire fed was too high in the two upper hybrid passes. The filling of the passes was favorable, *Fig. 4.33*, but the torch orientation had resulted in the fraction which lead to the bumpy weld bead for the last weld. This kind of surface of the previous weld is critical for the stable process of the following pass.

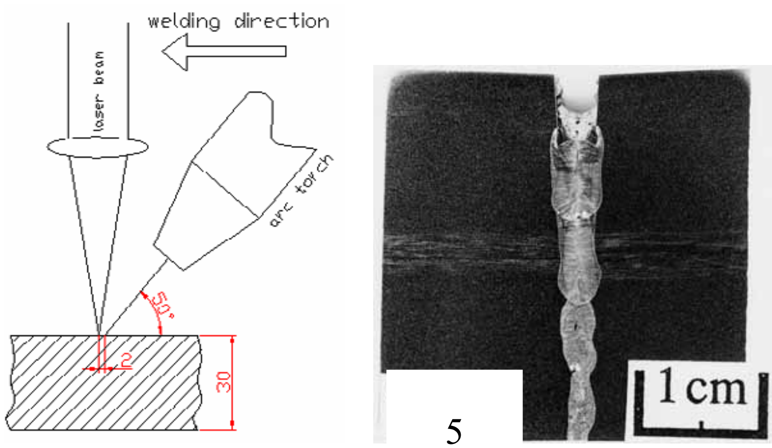


Figure 4.31. The set-up condition and cross-section of the weld with a thickness of 30 mm, testpiece 5. Parameters Appendix 6.

In order to achieve a proper adhesion between the passes, the laser beam and the arc should reach the surface of the previous weld. Accessibility of the process with narrow grooves depends mainly on the groove angle of the joint. *Fig. 4.32* shows that an 8^o groove angle is not enough for the process in accessing, although the parameters are selected carefully.

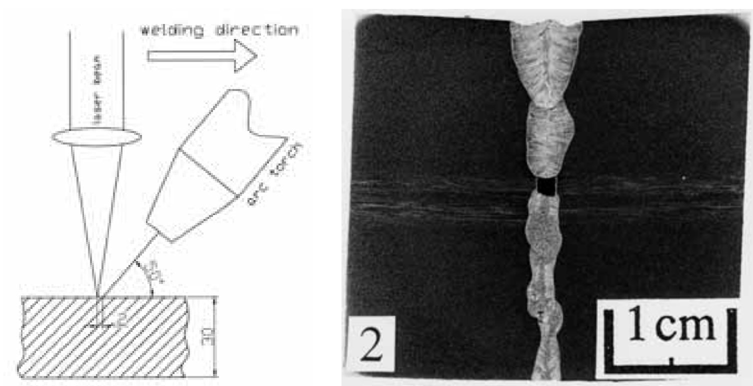


Figure 4.32. The set-up condition and cross-section of the weld with a thickness of 30 mm, testpiece 2. Parameters in Appendix 6.

Fig. 4.33 shows the filling in three different welds according to the individual passes.

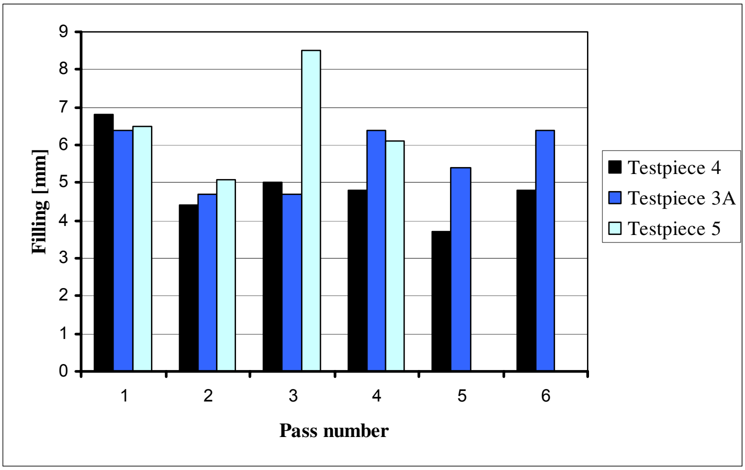


Figure 4.33. The filling of the individual passes in different welds of 30 mm thick plate, when the groove angle was 10°.

In hybrid welding, also quite rough filler wire feed rates can be used, if the groove allows it, *Fig. 4.34*. In the weld shown, the wire feed rate was from 13 up to 18 m/min and still the accessibility of the process was adequate for good adhesion.

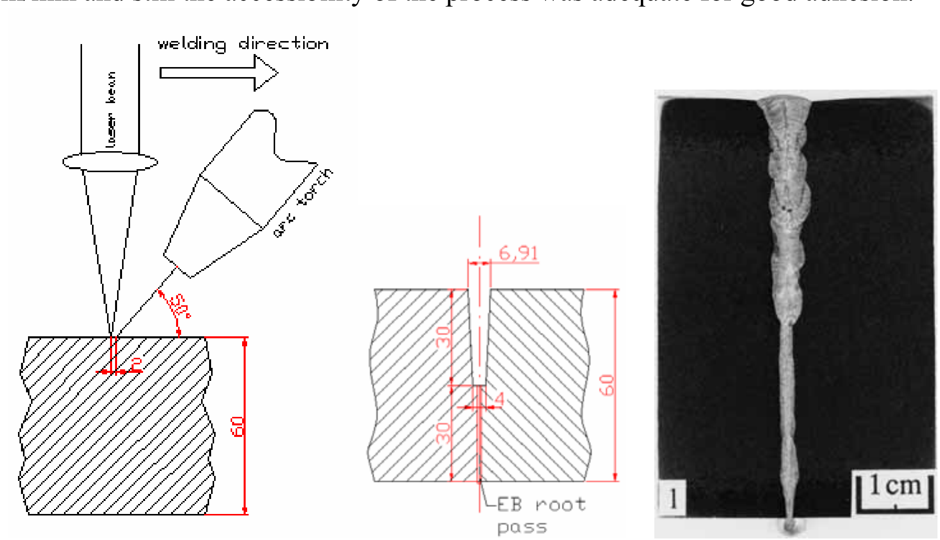


Figure 4.34. The set-up condition, groove geometry, and cross-section of the weld with total thickness of 60 mm, when a 30 mm root pass was made by electron beam welding. Testpiece 1. Parameters in Table 3.12.

5. Discussion

5.1 Single pass experiments

5.1.1 Laser welding with filler wire

In laser welding with filler wire a certain heat balance must maintain in order to produce sound welds. The balance consists the heat for melting the wire and sidewalls of the groove. In laser welding, the power needed for melting can be calculated according to the *Equation 5.1.*

$$P_L[1-(R+a_t)] = \rho V[C_p(T_m - T_o) + L_m] \tag{5.1}$$

in which

P_L = laser power [W], R = reflectivity, a_t = attenuation of the laser power, ρ = material density [kg/mm^3], V = volume in time [mm^3/s], T_m = melting temperature [K], T_o = room temperature [K], L_m = latent heat of melting [J/kg]

In laser welding with filler wire, the reflectivity R in *Equation 5.1* depends on the interaction between the laser beam and the filler wire and material of it. This means that set-up parameters, i.e. interaction point of the laser and wire, feed angle, focal point position, determine the reflectivity. When the laser beam is guided to the narrow groove together with filler wire, the wire absorbs part of the laser beam and also reflects some part, although in the case of Nd:YAG – laser the reflection is not playing major role due to its short wavelength. Due to the narrow groove the part of reflected laser power is also affecting to the process. Attenuation of the laser beam a_t means amount of the power, which is scattered from the metal plume above the keyhole and absorbed to it, although some amount of that power is affecting to the process as reflected power. Filler wire diameter, feed rate and the amount of sidewall melting determine the factor V in *Equation 5.1.* Due to that, heat balance between laser power in the process and amount of melted material should maintain. The other factors in *Equation 5.1.* are constant.

According to the Taguchi experiments, the most critical parameter range is for the focal point position with respect to the surface of the plate, *Table 4.2*. This was the case regardless of the result used in the calculation routine. The effect of the focal point positioning was 25% when the maximum welding speed with full penetration was the result in the calculation. The effect increased 6 percentage unit up to 31% when the result was the penetration effectiveness. The best value for the focal point positioning was in both cases 2 mm below the surface. At the lower welding speed, no dramatic change was noticed, if the focal point was positioned at the surface of the plate. However, when the welding speed was optimized, the effectiveness was increased and change to the other values was bigger. In both cases, when the focal point was raised over the surface, the penetration decreased dramatically. The above-mentioned arises from the fact that the laser beam looses its power intensity according to the focusing angle, especially with a higher welding speed it is important to use the highest intensity to create and maintain the keyhole at a stable state. The laser power intensity at the focal point was $1.1x10^4$ W/mm^2. This power density creates easily a stable keyhole, and thus deep and narrow welds. At a distance of 2 mm from the focal point the power density was $5.3x10^3$ W/mm^2, which still creates a keyhole. (Dawes, 1992) Considering the effect of the focal point position trough the *Equation 5.1* shows that when it is located inside to the groove, the part of the reflected and attenuated power is affecting to the process. When the focal point is located to the surface of the plate or above the power losses are higher.

When evaluating the effect of the interaction point, the best set-up was when the wire and the laser beam hit 2 mm below the focal point position inside the air gap of the joint, *Table 4.2*. The effectiveness of the interaction point was 14 and 21%, when the results were for the penetration effectiveness and the maximum welding speed, respectively, *Fig. 4.2*. The interaction point and its effectiveness depended on the focal point position. Although, the best place for interaction was defined to be 2 mm below the focal point, good results were also received when the wire was pointed at the focal point. However, in those cases the focal point was set at the surface or 2 mm below it. This means that liquid metal coming from the wire should be readily inside the groove, because when the interaction point is set-up above the focal position, the melted material from the wire seems to absorb the energy of the laser beam. The above-mentioned is in good accordance with literature. (Panten et al., 1990, Meinert et al., 2000)

The wire feed rate was calculated with respect to the groove volume using *Equation 2.1*. It was noticed clearly, that when the wire feed rate was increased above the groove volume the welding process became unsuccessful, especially in the case of the lower welding speed, and due to that the effectiveness was calculated to be 20%, *Fig. 4.2*. This indicates that an excessive amount of filler wire produces too much liquid metal in order to maintain a stable keyhole and especially liquid motion around it. According to that, there should be mentioned the equilibrium state between the air gap, the laser power and the amount of liquid metal. (Sasaki et al., 1986, Dahmen et al., 1999) The effectiveness of the wire feed rate decreased with increasing welding speed. The value, for the maximum welding speed was only 7.6%. This is in good accordance with phenomena discussed above. Increasing the welding speed produces less molten metal from the parent material, and better conditions predominate for the equilibrium state of the liquid motion and according to the *Equation 5.1* the power of the laser is more used to melt the wire.

Another great difference in the effectiveness of the parameters, when using different referring result was noticed in the filler wire feed angle, *Fig. 4.2*. In the case, when the penetration effectiveness was the result, the value was 1.9%, which is a negligible effect for the feed angle. When the maximum welding speed was used as a result, the effectiveness was fairly high, 21%. The difference is based on the absorption of the laser beam to the filler wire, *Equation 5.1*. With a lower welding speed, the size of the keyhole and molten area is bigger and thus giving the opportunity for the wire to melt, although it has not been melted directly by laser beam. This also allows more freedom in adjusting the wire to the laser beam. With the higher welding speed, the absorption plays a more important role, although good absorption of the Nd:YAG laser beam to the filler wire has been reported. (Salminen, 2001a) If the wire is not melted directly by laser beam, the smaller process point doesn't give any "backup" for melting. This also means tighter tolerances for adjusting the wire to the process. This can be seen in the results gained from the experiments when 20 and 60 degrees are concerned. It is more difficult to adjust the wire accurately with 60 degrees than with 20 degrees, which can be seen from lower result value of it, *Table 4.2*.

The optimal parameter combination received using the TAGUCHI test program creates the equilibrium state described above. The focal point positioning enables effective keyhole welding although the filler metal is fed to the process. The interaction point of the wire and laser beam does not disturb the process, and introduces the liquid filler metal at the optimal point in the joint (e.g. inside the groove), from which its motion around the keyhole starts. The energy absorbed from the laser beam to the liquid metal melts the surface of the joint before it solidifies behind the keyhole producing the weld. The filler wire feed rate is adjusted to fill the air gap of the joint without disturbing the process. Within the amount of filler wire, air gap and laser power, there is a dependency, which either produces the equilibrium state or not. Critical, in the point of view of the weld defect, is excessive feed of the wire. This collapses the maintenance of the keyhole and decreases the penetration. When the amount of filler metal is not enough to fill the gap, it can be clearly seen as a sagging of the weld bead, but an excessive amount produce incomplete penetration, which is not necessarily visible.

The optimal parameter combination was also confirmed by increasing the welding speed up to 0.6 m/min, *Fig. 5.1*. In autogenous welding of 6.8 mm thickness, the welding speed with a 3 kW Nd:YAG laser is 0.7 m/min producing a full penetrated, high quality weld. By using an optimal parameter combination, the decrease in the welding speed was then only about 14%, although a 1 mm air gap was to be filled.

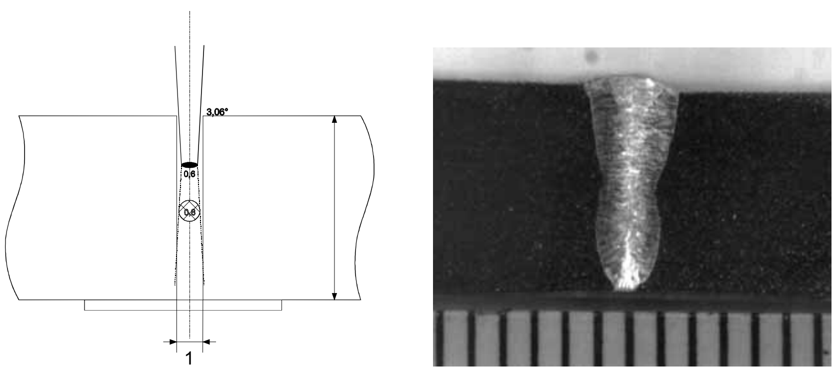


Figure 5.1. The set-up and cross-section of the weld made by the optimal parameter combination received from the single pass TAGUCHI experiments with filler wire. The welding speed 0.6 m/min. Weld OPTI 2. in Appendix 1.

5.1.2 Hybrid welding experiments

In the single pass hybrid experiments, it was clearly noticed that the welding speed for high quality welds, increased significantly, when comparing to plain laser welding or laser welding with filler wire. The welding speed was increased up to 0.9 m/min, which means 22% higher compared to autogenous and 33% to laser welding with filler wire. The reason for the raised welding speed was the auxiliary heat coming from the MIG, although parameters of that were at a moderate level, i.e. so-called short arc region. If the *Equation 5.1* is considered in the case of hybrid welding, the auxiliary heat and thus increased welding speed is expected because the power of the arc is added to the value P. Some changes can also happen in the reflectivity R because now the laser beam hits the filler wire which is already in the molten state. The amount of increase in welding speed is in good accordance with results reported in the literature. (Dilthey and Wieschemann, 2000, Abe and Hayashi, 2002, Nielsen et al., 2002)

During the experiments, another feature of hybrid welding was observed clearly; the stabilizing and guiding effect of laser beam for the arc. The MIG values were at a modest level, which can hardly produce sound welds even with thinner sections. However, with the addition of the laser, stable and calm process was observed. This stabilizing and guiding effect of the laser beam has been reported widely and is described in section 2.2. (Eboo et al., 1978, Steen, 1980, Ishide et al., 1997, Kutsuna and Chen, 2002, Ono et al., 2002)

From the cross-sections shown in section 4.1.2, it can be noticed, that the shape of the welds are uniform with the welds with filler wire or even with autogenous welds, i.e.the welds have parallel sided fusion zones. This shows that the welding has occurred through the keyhole process. This can also be seen in *Table 4.3*, in which the weld widths and the width/depth -ratio of the welds are shown. The values of the width/depth -ratio were between 0.32–0.52 and these are nominal for keyhole welding. The above-mentioned leads to the conclusion in agreement with literature referred in sections 2.2.2 and 2.2.5, that the auxiliary heat of the MIG has at least in some extent penetrated into the keyhole. In another way it can be said, that the laser-induced plume or liquid metal of the arc has not disturbed or absorbed the laser beam on its way towards the keyhole, although some attenuation could have happened. This phenomenon was noticed with both torch directions, and even though the angle of the arc torch was quite small.

When comparing the hybrid welds made by the Nd:YAG and CO_2 lasers, the difference in geometries is evident, *Figs. 2.18, 4.3–4.6*. The upper part of the CO_2 laser welds is wider, indicating uneven heat distribution during the process. This can be explained by the higher absorption of CO_2 -laser light into the plasma formed in the shielding gas by the laser itself and also by the arc. This problem with plasma leads to a higher value of distance D_{LA}, which decreases also the mutual effect of the processes. By using an Nd:YAG laser, the distance D_{LA} can be kept shorter, and the heat of the process is quite uniformly distributed to the whole thickness, and the advantages of the keyhole mechanism are not lost. The above mentioned indicates, that an Nd:YAG laser is very suitable for using in hybrid welding, which can also be concluded from the literature. (Abe and Hayashi, 2002, Ishide et al., 2002, Kutsuna and Chen, 2002)

The distance D_{LA} should still exist to ensure a sound process, especially in the case of the leading edge torch orientation. When the torch orientation was the trailing edge, the distance could be shorter or even zero, *Figs. 4.3, 4.5*. In that case, the arc was discharging to the hot molten surface of the weld behind the impingement point of laser beam and thus did not disturb the keyhole. The disturbing effect, which comes from the arc pressure, cannot then have an influence on the balance of keyhole, but it influences the liquid metal. If the arc pressure is pointed too near to the keyhole in the leading edge torch orientation, the keyhole collapses from its leading edge, causing a decrease in the penetration and weld defects.

In adjusting the parameters for the successful process of single pass hybrid welding, one suitable tool is *Equation 2.1*. Due to that the filler wire feed rate can be preliminary adjusted, and with modern arc welding machines, the other arc parameters are synergetic chosen by the machine. For the joints used in the experiments the calculated value of the filler wire feed was 9.75 and 12.5 m/min, with the welding speed of 0.7 and 0.9 m/min respectively. This also shows the wide area of parameters usable for a sound process.

5.2 Multi pass experiments

5.2.1 Laser welding with filler wire

5.2.1.1 Root pass

In laser welding of thick sections with a multi pass technique, the most critical part of the procedure for the root welding is the accessibility of the laser beam to the bottom of the groove. First of all the groove geometry used has to allow clear passage of the laser beam according to the focusing geometry of the laser beam. The selection of the geometry, especially when welding from one side only also depends on distortions of the plates during welding. Another factor affecting the selection is the productivity of the process, which increases with decreasing groove area, and in the case of a bevelled groove, the angle of it.

In the experiments it was noticed that Nd:YAG laser welding using the given focusing optic and procedure, is applicable for the root welding of a partially grooved V -joint with a groove angle of 8^{o}. This angle allowed the accessibility of the laser beam during the whole welding sequence. The angle is smaller than has been used with laser welding especially with CO_2 lasers. (Atsuta et al., 1988, Panten et al., 1990, Dahmen et al., 1999) The reason for this comes partly from the procedure used, in which quite a thin root weld is produced. Also the enabling thing for using a narrower groove is the shorter wavelength of the Nd:YAG laser. In laser welding the plasma is formed above the keyhole and when it appears in narrow groove, it can block the beam of the CO_2 laser, which is absorbing to it. In a narrow groove this plasma cloud is difficult to blow away and also in a narrow groove the hottest spot is raising and melting happens in the upper region of the groove. Owing to the shorter wavelength, the beam of Nd:YAG laser behaves differently as discussed in section 2.25. Although some attenuation of the beam may happen, absorption does not happen and the beam and thus the process is able to go to the bottom of the groove.

Normally the thick section laser welding procedure has been carried out in a way that the root pass is maximized according to the laser power. *Fig. 5.2* shows the edge preparation examples for welding 25.9 mm thick mild steel with a CO_2 laser power of 20 kW. The root face has been maximized up to 16 mm. (Dahmen et al., 1999)

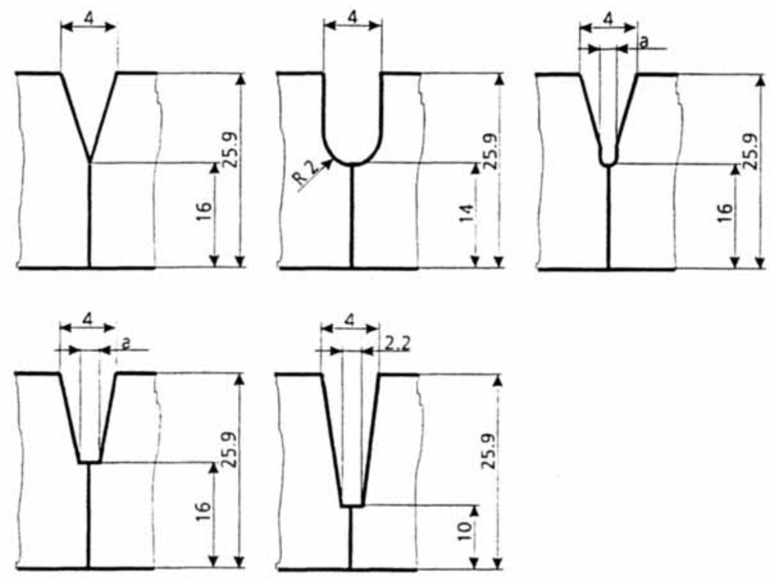


Figure 5.2. The edge preparation examples for multi pass CO_2 welding of a thickness of 25.9 mm (Dahmen et al., 1999).

In the welding experiments of the root pass for joints shown in the upper row in *Fig. 5.2*, the main drawback was the formation of a surface crack in the upper bead of the root pass. This was coming from the weld distortions during welding, when strong longitudinal forces were introduced into the walls of the joint. By the sharp-edged transitions the lines of force are necked-in, which leads to a high concentration of tensile forces at the center of the upper bead. The authors overcame the problem using the joint shown in the lower row of the *Fig. 5.2*, i.e. T-preparation and larger opening of the groove. This formed a slightly concave upper bead formed with tangential connections from the bead to the walls of the groove. Discontinuities of the lines of force are avoided and their transitions became smooth, which leads to an advantageous stress distribution within the seam and surrounding material. (Dahmen et al., 1999)

Due to the hot-cracking susceptibility of austenitic stainless steel, the crack formation was taken into account in the experiments. Although a partially grooved V-joint was used in the experiments of this thesis, still crack-free in the upper beads of the root welds were produced. The main reasons for this were the relatively small root face used and the use of the air gap between the plates. The shape of the weld bead produced by this procedure was advantageous and the stresses were not highly concentrated on the root weld bead. Also the shape of the root weld bead was favorable for the first filling pass coming after the root weld. The quite simple groove geometry introduced affects strongly on the manufacturing costs of the groove, because of the easier machining.

In the experiments it was noticed that by using a 4 mm parallel root face with an air gap of up to 1 mm, the penetration and defect free weld was ensured. The depth of the root face is related to the laser power used. With 3 kW Nd:YAG laser power it is possible to weld 7 mm thick plates with a welding speed of 0.5 m/min using a filler wire and an air gap. Still at the bottom of the narrow groove the depth of the root face should be kept at the lower level because of the heat conduction from the root to the upper region of the material. Using a 4 mm root face heat conduction is a concern so some reserve has been left for the laser power to enlarge the parameter window. Although the root face was restricted, still the welding efficiency of the keyhole mechanism of the root weld was high compared to the root weld made by conduction laser welding with considerable higher power of 11 kW, *Fig. 2.8*. (Coste et al., 2001b)

Although the root weld shown in *Fig. 4.7* was made with a testpiece of 20 mm in thickness, the same groove geometry could also be applied to the thicker sections. With this geometry, the main thing for successful root welding with a laser and filler wire was fulfilled; the accessibility of the laser beam to the bottom of the root. Introducing the filler wire to the bottom of the groove demands a smaller diameter for the filler wire than the air gap between the plates. By using smaller filler wire the stable "bridge" discussed in section 2.1.2 was formed and the process was stable and producing acceptable weld quality. (Sasaki et al., 1986, Dawes, 1992)

5.2.1.2 First filling pass

The crucial factor in welding of the first filling pass by laser with the filler wire is that the weld has to melt the surface of the previous root pass as well as the surfaces of the groove. This demands good accessibility of the laser beam and also a stable and appropriate flow of liquid material around the keyhole formed by the laser beam.

When considering the accessibility of the laser beam, the same factors have an affect as for the welding of root pass. The main thing for the successful process is the location of the filler wire according to the focal point of the laser beam, i.e. the interaction point. When this point is optimized, the amount of filler wire fed can be maximized and the filling effect of the pass and the efficiency of the process are the highest. The best results were achieved when the filler wire was pointed 2 or 4 mm below the focal point position. When the interaction point was in the focal point position, the weld defects like poor adhesion to the root weld were noticed, *Fig. 4.12*. This indicates that the filler wire fed to the process blocked the way of the laser beam. In these cases it was noticed that the process became unstable and produced increased spattering with poor surface quality of the weld, *Fig. 5.3*. In multi pass welding these affect negatively on the stability of the process of the following filling pass.

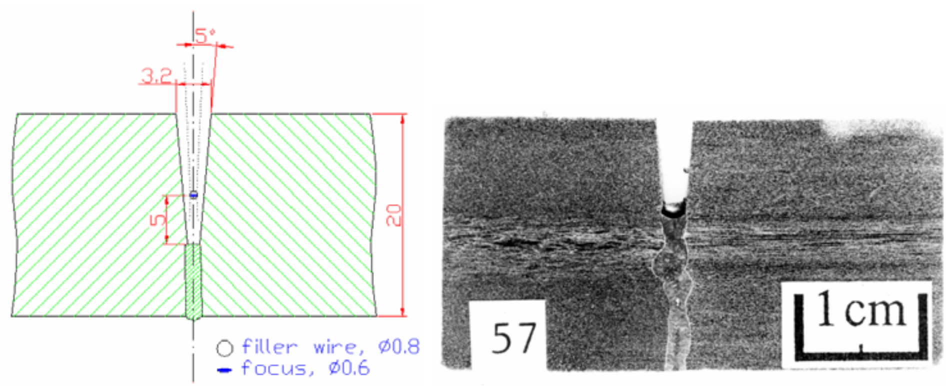


Figure 5.3. The set-up and cross-section of the filling weld, testpiece 5.7. Parameters in Appendix 2.

Another blocking effect was noticed when an excessive amount of filler wire was fed to the process. The amount of filler wire fed was in connection with the groove angle and the focal point position, because the filler wire feed rate was calculated with *Equation 2.1*, in which the groove area used was formed by the groove surfaces and the focal point. This feed rate was decreased by 10, 20 and 35%. It was noticed clearly that when the amount of filler wire decreased the accessibility of the laser beam increased, *Fig. 4.13*. In the other way, when the amount of filler wire increased poor quality welds were produced according to the adhesion of the root weld, *Fig. 4.8*. For the same reason, the focal point position in which it was raised 7 mm from the surface of the root pass was not producing acceptable quality welds, *Fig. 5.4*.

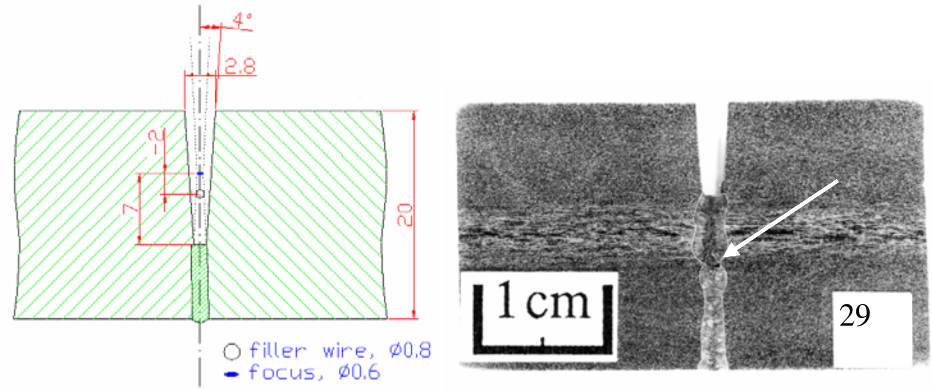


Figure 5.4. The set-up and cross-section of the filling weld, testpiece 2.9. Poor adhesion between the passes is marked with an arrow. Parameters in Appendix 2.

When the amount of the filler metal fed was at the proper level according to the groove area, i.e. the groove angle and focal point position, a sound and stable process was observed. In those welds, for example *Figs. 4.10, 4.11 and 4.13*, real keyhole welding occurred with a stable and appropriate flow of liquid metal around the keyhole. The keyhole effect is clearly visible in the figures of the cross-sections and also in the filling of the passes, *Table 4.4*. The structure of the flow around the keyhole, which is in the groove, is of a flow of molten metal from the wire feed on the leading edge of a keyhole, which consists of a metal vapour. The heat from the laser absorbs and reradiates from the gases and together with the moving liquid material at the edges of the keyhole, melts the walls of the narrow groove. And after the keyhole molten metal solidifies to become the weld. So although the air gap at the welding point of the first filling passes is from 1.5 up to 2.0 mm, still a stable flow of liquid material, described in section 2.1.2 is possible. (Sasaki et al., 1986, Dawes, 1992)

5.2.1.3 Filling passes for thicker sections

While in the case of the root pass and the first filling pass the critical factor was the accessibility of the laser beam, it was not the case in the filling passes of the upper section of the groove. With the filling passes the critical thing was the melting capacity of the filler wire, which comes directly from the power of the laser. Also the power of the laser affects on the maximum plate thickness, which can be welded using the keyhole mechanism. In the narrow groove the pressure of the keyhole keeps the melted material from the filler wire and from the parent material on the walls of the groove. This hot material melts the groove surfaces together with the laser beam. This means that the amount of filler wire should be in connection with the groove volume, i.e. groove area.

In the experiment a partially grooved V joint was used with groove angles of 8^o and 10^o. With 3 kilowatt Nd:YAG laser power using the groove geometry mentioned, the limits for the thickness to be welded were from 18 to 21 mm in the case of a groove angle of 10^o, while it was from 21 to 24 mm with 8^o groove angle. The determining factor is not directly the thickness, but the air gap at the point of the weld is. This can be seen in *Fig. 4.17*, in which a 35 mm thickness is welded with a groove angle of 8^o but the angle has decreased after every individual weld due to the distortions. If the angular distortions are restrained, the limit for the air gap was found to be about 2.8 mm. Above this value the amount of filler wire, which is needed to fill the groove, exceeds over the limit of the 3 kW Nd:YAG laser. The power of the laser is used for melting the wire and also to produce the keyhole, which pressure keeps the molten metal towards the groove surfaces and thus provides melting of the surfaces and a stable process according to the flow of molten metal. Comparison of the mentioned air gap 2.8 mm with the values in *Fig. 2.5* indicates the supporting effect of the groove and especially the previous pass to the increased amount of molten metal.

Use of a 3 kilowatt Nd:YAG laser for welding with filler wire for a larger air gap than 2.8 mm in the narrow groove needs widening of the laser beam for example by oscillation or defocusing. However, when the beam is widened with the same power the intensity decreases and keyhole welding is not possible any more due to the collapsed pressure formed by the laser. Then the welding phenomenon converts to conduction welding. This leads to wider welds with poor penetration. This means more passes and more total heat input to the joint, which in turn affects on the distortions and efficiency of the process. (Dahmen et al., 1999, Coste et al., 2002)

The parameters used in the multi pass experiments were derived from the results of the root and first filling pass experiments, because the same factors are affecting also in the multi pass welding. The main point for the successful process is the interaction point of the wire and the laser beam, which should exist under the focal point. One aid in the welding with a narrow groove is the guiding effect of the groove surfaces on the wire, which ensures the horizontal placement, W_Y of the wire, *Fig. 2.2*. The tolerances for the horizontal placement are in good accordance with reported results and show the difference between the CO_2 and Nd:YAG laser on absorptivity. (Meinert et al., 2000, Salminen, 2001b)

5.2.2 Hybrid welding

In the TAGUCHI experiment for the first filling pass, the effects of four different parameters were studied for the stable and effective process. The stability of the process in the first filling pass is important for the quality of the weld because the conditions for welding are the most stringent, i.e. narrow groove and the welding happens at the bottom of it. Thus the most important factor once again is the accessibility of the laser, arc and filler material to the point of welding. When welding following filling passes, the air gap in the groove is larger and then the accessibility does not play such a major role. In the case of upper passes the stable flow of excessive molten metal around the keyhole is required. This still needs the balanced behaviour of the keyhole, which comes from adequate pressure inside it.

5.2.2.1 The TAGUCHI experiment for the first filling pass

Distance between the laser beam and arc D_{LA}

As mentioned above, the most critical factor for the successful hybrid welding of the first filling pass in a narrow groove is the accessibility of the process. According to the TAGUCHI experiment the most effective parameter changed in the experiment for accessibility is the distance D_{LA} between the laser point and arc. The effectiveness of it was 43.4%, *Fig. 4.22*. It was clearly noticed that the welding process became more stable if a certain distance between the laser focal point and the discharge point of the arc was applied. According to the stable process, fewer defects were found and also the filling effect was better. The optimum value of the distance D_{LA} was 3 mm, but there was no big difference between it and another tested, 1.5 mm. The results achieved for distance D_{LA} are in good accordance with literature. (Ishide et al., 2002, Abe and Hayashi, 2002, Kutsuna and Chen, 2002)

The successful hybrid welding demands a mutual interaction between the laser beam and the arc. Although the mutual interaction is needed, still the stability of the process collapsed when the laser beam and the point of arc were combined to the same spot. This was noticed during the welding and also from the quality of the welds; poor adhesion and lack of fusion were noticed in cross-sections. By displacement, of up to 3 mm of the beam and the arc, the stability of the process was improved. This means, that when the impingement point is the same, the laser energy is used in melting the wire in the formation of the keyhole and penetration of the weld is decreasing. Also an increased amount of molten metal at the interaction point is decreasing the penetration. When this happens inside the narrow groove the critical weld defects will result in the form of poor adhesion and lack of fusion. At the other end there is also a limit for the distance D_{LA}. When the distance is increased excessively, the plasmas are separated and the penetration is coming only from the laser power and no mutual effects of the hybrid process exists, *Fig. 2.19*.

Wire feed rate, W_R

In the preliminary experiments it was noticed clearly that, if *Equation 2.1* was used for calculating the amount of filler wire to be fed to the narrow groove, it was too much and led to the unstable process and poor adhesion of the weld to the previous one. Thus in the TAGUCHI experiment values of 40, 50 and 60% of the calculated amount of filler wire feed was used, *Table 4.6*. The best value was received with 50%, but the difference with 40% was only 0.03 points. The effectiveness on the process was little, i.e. 14.9%, *Fig. 4.22*. Although rather small effectiveness, it was noticed clearly that in order to receive high quality welds, too much filler metal should not feed to the narrow groove, especially in the case of the first welds. If too much filler metal is fed, it gets in the way of the laser beam and not enough energy goes to the surface of the previous weld and poor adhesion results. If too an excessive amount of filler metal is fed and the distance D_{LA} is zero, the process collapses totally, *Figs. A7–6 and A7–8 in Appendix 7*. So the proper distance D_{LA} maximizes the amount of filler wire fed.

One reason for a small feed rate is also the difficulty in ensuring the weld quality. If too excessive amount of filler wire is fed to the laser welding with filler wire, the wire does not melt properly and it can be seen clearly immediately. This is not the case in the hybrid welding. If the amount of filler wire is too much for the groove used, the arc voltage and current raised due to the control of the welding machine and the process seems to be stable but still there can be serious defects in the weld, like is shown in *Fig. 4.32*.

As can be seen from the arc parameters used in the TAGUCHI experiment, it can be said that values were at a quite moderate level, i.e. in the short arc region. The experiment showed clearly the possibility for a stable hybrid process, although the arc parameters are so low, they could hardly make a weld by the arc alone. Low arc parameters were due to the low filler wire feed rate used, according which the newest MIG welding machines with the synergized control adjusts the arc parameters.

Focal point position, f

According to the groove geometry measured after root pass and the focal point position used in the experiment, the amount of filler wire to be fed was calculated by using *Equation 2.1*. Thus the effectiveness of the focal point position is increased, because it also affects on the amount of filler wire introduced to the process. The effectiveness was 17.8% and the best value received from the TAGUCHI experiment was a 7 mm raise from the root pass, *Fig. 4.22*. Also good results were achieved with a raise of 5 mm, and according to the adhesion to the root pass even better, *Figs. A7–1, A7–4 and A7–7*. But due to the pointing system of the results, the filling effect was more dominating and the effect of the adhesion was only slight. A 9 mm raise from the root pass was too high for two reasons; the filler wire feed rate was too high for the laser to melt it and also for the laser power intensity would be too low at the surface of the root pass, *Fig. A7–9*. In order to maintain a stable process of hybrid welding inside the bottom of the narrow groove, the laser should produce quite sharp spot on the surface of the previous pass. Due to that, the stabilizing and contraction effect of the laser beam, which is described later, is able to exist.

Torch orientation, D_t

According to the TAGUCHI -results made with the first filling pass, the trailing edge torch orientation is better for the filling effect. Despite that, during the experiments it was noticed that the trailing edge orientation was more sensitive to disturbances in the process, especially if the amount of filler metal fed increased. The process made spatters more and also the discharging point of the arc was in some cases unstable. This is coming from the fact that arc pressure is aiming at the molten metal and if high arc parameters are used, i.e. the arc pressure is high, some spatters can fly from molten metal. Also the pressure can impel the molten metal towards the keyhole. Still, if the filler wire feed rate was adjusted correctly and there was some distance between the laser focal point and arc, a sound and stable process, and high quality welds were still achieved, *Fig. A7–4*. After the calculation routine of the TAGUCHI experiment, a high value was received for the arc orientation in the mean of effectiveness to the process, 26.6%, but no big difference was noticed between the trailing and leading edge orientation, *Fig. 4.22*. The value for the leading edge was 3.92 when it was for the trailing edge 4.13, *Table 4.6*.

Optimal parameter combination

Due to the pointing system, which is described in section 4.2.2.1, the filling effect was a more critical factor than the effect of the adhesion between the passes. This resulted an inadequate adhesion between the root pass and first filling pass for a weld, which have been made with an optimal parameter combination, *Figs. 4.20 and 4.21*. Another reason for the poor adhesion was improper adjustment between the arc and the laser beam, which can be noticed from two matters. First, from the weld cross-sections in *Figs 4.20 and 4.21* it can be seen that the welds are more or less orientated to one side of the groove. Second, the proper adhesion is seen in *Fig. A7–5*, although the weld has been made with the same optimal parameter combination, but the torch orientation is now on the leading edge.

Another matter in the TAGUCHI calculation routine is that the optimal parameter combination is formed from the actual values used in the experiments and does not take account of the values between the chosen ones. For example when looking at the calculation routine of the wire feed rate W_R, it can be noticed that the difference between the 40% and optimal 50% is much smaller than the difference between 50% and 60%, *Table 4.6*. This indicates that the real optimal value is between 40% and 50%.

5.2.2.2 Process phenomena

The stability of the process in the first filling pass is important for the quality of the weld because the conditions for welding are the most stringent, i.e. narrow groove and the welding happens in the bottom of it. Thus the most important factor is the accessibility of the laser, arc and filler material to the point of welding. One of the most important factors in introducing a hybrid process inside a narrow groove is the contraction effect of the laser towards the arc. This is shown in *Fig 2.17* and described in section 2.2.1. (Steen, 1980, Ono et al., 2002) If the arc is introduced to the narrow groove alone, the arc is prone to instability and the discharging point will be either at the groove surfaces or at the edge on the surface of the metal and groove.

The above-mentioned is in connection with the transmission and its mode of the filler wire of an arc. A smooth molten droplet transfer, which secures the quality of the weld is active in hybrid welding. And this is happening because of the contraction of the laser on the arc. Normally in arc welding the thermionic point on the plate to be welded is moving and the energy of it is widely dispersed. In hybrid welding the laser radiation point (and in this case deep inside the narrow groove) is acting as a thermionic point and thus discharging point of the arc. So the arc is squeezed into a narrow range and concentrates the energy. Therefore, the wire is easily melted, the arc length is short, so the droplets become small and are transferred to the process at a high frequency. A smooth droplet transfer is possible with plain arc welding only at high values of arc current and voltage. This means that in hybrid welding quite small values can be used in order to get a favorable form of the droplet transfer. (Ono et al., 2002, Kutsuna and Chen, 2002, Makino et al., 2002, Minami et al., 2002)

The stabilizing effect of the laser beam to the arc, described in section 2.2.1, plays also an important role for a successful process. When the laser beam hits the surface of the root pass, a keyhole is starting to be formed. The electron density in the keyhole reaches 10^{17}–10^{20} / cm^3 and surrounding area is in a molten state, so thermionic emission takes place very easily. Thus, when arc welding is combined with laser welding within this region, a stable arc is maintained despite of the small displacement between the arc and laser beam, *Fig. 2.14*. This phenomenon of the keyhole to the arc keeps the discharging point stable and properly situated. The stabilizing effect impacts upon the welding procedure; at the beginning of welding inside a narrow groove, the laser should be put on just before the arc. By doing this the placement of the arc is secured. (Eboo et al., 1978, Ishide et al., 1997, Makino et al., 2002, Ono et al., 2002)

The cross-sections of the welds in section 4.2.2 and the measurements in *Fig. 4.28*, indicate strongly that welding has occurred through keyhole welding. This means that the existence of the arc has not disturbed the laser beam and maintenance of the keyhole and the auxiliary heat coming from the arc is penetrated to the keyhole, as discussed in section 5.1.2. This leads to the conclusion that not only the heat of the laser beam is affecting inside the keyhole, but also the heat of the arc. This kind of mutual behavior is more pronounced with short wavelength of an Nd:YAG laser. (Abe and Hayashi, 2002, Ishide et al., 2002, Nakajima et al., 2002, Ono et al., 2002) The above-mentioned can also be concluded from the groove angles used in this work and reported angles with hybrid welding with a CO_2 laser, see section 2.2.4. The reported, partially grooved V-joints have had the groove angle starting from 25^o while in this work acceptable results were achieved with a groove angle of 10^o. (Hyatt et al., 2001, Makino et al., 2002, Minami et al., 2002) The reason for wider grooves is coming from the absorptivity of the plasma for CO_2 laser beam. Due to this plasma appears above the welding point and the beam increases its heat and the discharging point of the arc is raised. By this feature, which is described in section 2.2.5, the process does not reach the bottom of the groove and lack of fusion between the passes exists. (Nakajima et al., 2002)

5.2.2.3 Filling passes for thicker sections

All the above-mentioned features of the hybrid process inside the narrow groove are the key effects also for welding of upper sections of the grooves. However, the circumstances are different according to a larger air gap in the groove. Thus in the case of upper passes the stable flow of excessive molten metal around the keyhole is demanded and accessibility does not play so an important role. Still balanced behavior of the keyhole is required, which comes from the adequate pressure inside it.

As in laser welding with filler, which is described in section 5.2.1.3, the main thing in welding of the upper regions of the narrow grooves is the air bridging ability and the equilibrium state of the flow of molten metal around the keyhole. When comparing laser welding with filler wire the air bridging ability is higher with hybrid welding. In welding with filler wire the limit of the air gap in the groove was defined as 2.8 mm, when it was pointed out to be about 7 mm with hybrid welding, *Fig. 4.34*. An air gap of 7 mm means a thickness of 38 mm if a partially grooved V-joint is used with a groove angle of 10^{o} and a parallel root face of 4 mm. In the welding of testpiece 1 with electron beam welded root, the thickness welded by hybrid welding was 30 mm. The groove geometry was wider than with the other testpieces. Due to that, the filler wire feed rate exceeds up to 18 m/min. This amount of filler wire is not able to melt using only a 3 kW Nd:YAG laser at a welding speed of 0.5 m/min.

The favorable phenomenon of hybrid welding is that by using synergetic control of the MIG/MAG machines, the arc parameters are increasing respectively. Thus the increase in the air bridging ability is coming from the extra heat introduced by the arc. The filler metal to be fed to the process is in molten form already. Another favorable effect of the extra heat coming from the arc is the increase in the diameter of the keyhole, *Fig. 2.20*. Also because of the uniform heat distribution of the arc inside the keyhole, the pressure of it is increasing also. So, the pressure inside the keyhole is enough to keep the molten metal, which is flowing around the keyhole towards the surfaces of the groove. Also the support of the previous pass plays an important role as well as the welding speed, which can be kept at a reasonable level and thus affecting on the stable flow of molten metal.

The above-mentioned affects also on the filling of the passes. That is because the filling of an individual pass is not decreasing like it is in laser welding with filler wire, when welding the upper sections of the groove, *Figs. 4.26, 4.33*. Although the amount of filler wire fed to the process is increasing the penetration is maintained and the melting of the previous pass and the groove surfaces occur.

The overlapping of the filling pass to the former one of about 2 mm, produces acceptable welds, *Table 4.7*. The amount of overlapping is based on the parameters, which control the penetration, e.g. the focal point position, the amount of filler wire, the interaction point etc. The unstable behavior of the arc was clearly noticed when the torch orientation was the trailing edge. In that case the arc was prone to change the discharging point to the upper sections of the groove and this affects dramatically on the penetration of the weld and can cause critical lack of fusion between the passes, *Fig. 4.30*. Normally due to the smooth droplet transfer in a very short cycle, the hybrid welding can provide uniform beads even inside the narrow groove and even with a relatively high welding speed. This affects favorably on the welding of the following pass. Still it was noticed that if the above-mentioned wandering of the arc discharging point upwards occurs, the bead shape can be fluctuated and the circumstances for the following pass are difficult. Although the accessibility of the process is easier after the first filling pass, still it was noticed to cause breakdowns. According to this, the minimum groove angle was defined to be 10^{o} when using a partially grooved V-joint, also in the upper regions of the grooves.

6. Conclusions

In this work the laser welding with filler wire and the hybrid welding were used in the welding of thick section austenitic stainless steel for a very narrow gap and using a multi pass technique. By the help of the characteristic features of the Nd:YAG laser both processes were able to enter the energy inside the narrow groove. By using the narrow groove with procedures shown in this work the number of passes can be decreased significantly and the efficiency of the welding can be increased.

On single pass experiments with a plate thickness of about 6.5 mm the characteristic factors for both processes were studied. The experiments showed the gap bridging ability, which can be used also for multi pass welding. In the experiments keyhole welding was observed in both laser and hybrid welding inspite of the existence of the arc. Due to that the welding speed could be raised from 0.5 m/min up to 0.9 m/min.

The main point in the multi pass experiments was to study the applicability of the processes to a narrow groove. It was noticed that applicability is dependent on the accessibility of the energy to the bottom of the groove. From such reasoning the minimum groove angle can be defined. Experiments showed that laser welding with filler wire could be achieved with a groove angle of 8^o, while stable hybrid welding is possible for the first filling pass with an angle of 10^o. The welding procedure shown consists of a root pass with the laser and filler wire and welding of the upper sections of the groove with more efficient hybrid welding. Use of this procedure is flexible since it is possible to use the same machine for filler wire feeding, i.e. with the root weld arc is turned off, while for the upper sections it is turned on.

The maximum thickness shown in this work was 20 mm for the laser welding with filler wire and 30 mm for the hybrid welding. The main factor for the thickness is the groove geometry and the groove angle, which together with the thickness determine the air gap at the surface of the material and vice versa. Applicability of the processes used is defined by the maximum air gap in the joint.

The procedure introduced in this thesis is based on the use of a 3 kW Nd:YAG laser with a focusing optic of 200 mm. Use of the procedure with different Nd:YAG lasers is possible, but the groove geometry will vary according to the focusing optic. Continuously the lasers are developed and new types of lasers are introduced. The development is aimed at the higher laser power with better beam quality. This allows in the future the use of even narrower grooves and thus a more efficient process.

In the point of view of the industrial feasibility, laser welding has suffered high demands of groove manufacturing and fixturing of the components to be welded. By using filler wire in the process the feasibility increases together with the gap bridging ability. The use of hybrid welding extends the joint tolerances to a new level together with the increased welding speed. Increased welding speeds is not the only reason for the interest of industrial use of these processes, but also reduction of the distortions and thus a time consuming work phase after welding. The same applies for multi pass welding of thick section steels.

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Appendix 1: Parameters used in the single pass welding experiments with filler wire

Constant

Material	AISI 316LN	Filler wire	OK16.32
Groove	I	Filler wire diameter	0.8 mm
Air gap	1 mm	Shielding gas	He, 14 l/min
Laser power	3 kW	Focal point diameter	0.6 mm
Focal length	200 mm		

Variable

Weld	Welding speed [m/min]	Wire feed rate [m/min]	Interaction point [mm]	Feed angle [^{o}]	Focal point position [mm]
1.	0.5	5.35 (V_L-10%V_L)	-2	20	-2
2.	0.5	5.35 (V_L-10%V_L)	0	40	0
3.	0.5	5.35 (V_L-10%V_L)	2	60	2
4.	0.5	5.95 (V_L)	2	20	0
5.	0.5	5.95 (V_L)	-2	40	2
6.	0.5	5.95 (V_L)	0	60	-2
7.	0.5	6.55 (V_L+10%V_L)	0	20	2
8.	0.5	6.55 (V_L+10%V_L)	2	40	-2
9.	0.5	6.55 (V_L+10%V_L)	-2	60	0
Opti 1.	0.5	5.35 (V_L-10%V_L)	2	40	-2
Opti 2.	0.6	6.45 (V_L-10%V_L)	2	40	-2

Appendix 2: Parameters used in the multi pass experiments with filler wire and a material thickness of 20 mm

Constant

Material	AISI 304LN	Filler wire	OK16.12	Laser power	3 kW
Groove	Partially grooved V	Filler wire diameter	0.8 mm	Focal point diameter	0.6 mm
Air gap	0.85 mm	Shielding gas	He, 18 l/min	Focal length	200 mm
Parallel root face	4 mm	Welding speed	0.5 m/min	Feed angle	45°

Variable

Weld	Groove angle [°]	Wire feed rate[m/min]	Interaction point [mm]	Focal point [mm]	Note
1.1	8	6.5 (V_L-10%V_L)	-4	-8	First filling pass
6.2	10	8.2 (V_L-10%V_L)	-2	-6.7	First filling pass
3.3	12	10.9 (V_L-10%V_L)	0	-6.2	First filling pass
3.4	12	6.1 (V_L-20%V_L)	-2	-8.2	First filling pass
1.5	8	7.3 (V_L-20%V_L)	0	-7	First filling pass
6.6	10	8.9 (V_L-20%V_L)	-4	-5.7	First filling pass
5.7	10	4.7 (V_L-35%V_L)	0	-7	First filling pass
4.8	12	6.3 (V_L-35%V_L)	-4	-7.3	First filling pass
2.9	8	6.7 (V_L-35%V_L)	-2	-5.6	First filling pass
1.					
I	10	5.0	-2	-13	Root pass
II	10	5.5	-2	-8	First filling pass
III	10	6.0	-2	-5	Second filling pass
2.					
I	10	4	-2	-15	Root pass
II	10	4	-2	-9	First filling pass
III	10	5.5	-2	-6	Second filling pass
IV	10	5.5	-2	-3	Third filling pass
V	10	5.5	-2	-1	Fourth filling pass
3.					
I	10	4.5	-2	-13	Root pass
II	10	4.5	-3	-8	First filling pass
III	10	4.5	-4	-5	Second filling pass
IV	10	4.5	-4	-1	Third filling pass
V	10	5.5	-4	2	Fourth filling pass
VI	10	1.5	-4	4	Fifth filling pass

Appendix 3: Parameters used in the multi pass experiments with filler wire and a material thickness of 30 and 35 mm

Constant

Material	AISI 304LN	Filler wire	OK16.12	Laser power	3 kW
Groove	Partially grooved V	Filler wire diameter	0.8 mm	Focal point diameter	0.6 mm
Air gap	0.85 mm	Feed angle	45^{o}	Focal length	200 mm
Parallel root face	4 mm	Welding speed	0.5 m/min		

Variable

Weld	Groove angle [^{o}]	Wire feed speed [m/min]	Interaction point [mm]	Focal point [mm]	Shielding gas [l/min]	Note
2.						
I	8	3.5	-2	-30	Ar, 18	Root pass
II	8	4.5	-2	-25	Ar, 18	First filling pass
III	8	5.5	-2	-20	Ar, 18	Second filling pass
IV	8	6.0	-2	-16	Ar, 18	Third filling pass
V	8	6.0	-2	-12	Ar, 18	Fourth filling pass
VI	8	4.5	-2	-8	Ar, 18	Fifth filling pass
VII	8	4.5	-2	-3	Ar, 18	Sixth filling pass
VIII	8	4.5	-2	0	Ar, 18	Seventh filling pass
3.						
I	10	4.5	-2	-13	He, 18	Root pass
II	10	4.5	-3	-8	He, 18	First filling pass
II	10	4.5	-4	-5	He, 18	Second filling pass
IV	10	4.5	-4	-1	He, 18	Third filling pass
V	10	5.5	-4	2	He, 18	Fourth filling pass
VI	10	1.5	-4	4	He, 18	Fifth filling pass

Appendix 4: Parameters used in the TAGUCHI experiments with hybrid welding for the first filling pass

Constant

Material	AISI 304LN	Filler wire	OK16.12	Laser power	3 kW
Groove	Partially grooved V	Filler wire diameter	0.8 mm	Focal point diameter	0.6 mm
Air gap	0.85 mm	Torch angle	50°	Focal length	200 mm
Parallel root face	4 mm	Welding speed	0.7 m/min	Shielding gas	He, 16 l/min (extra nozzle)
Groove angle	10°				Ar, 7 l/min (MIG torch)

Variable

Weld	Wire feed rate [m/min]	Distance D_{LA} [mm]	Focal point [mm]	Torch orientation	Arc voltage [V]	zArc current [A]
1	5.3 (40% V_I)	0	5	Leading	21.9	81
2	8.3 (40% V_I)	1.5	7	Leading	17.4	71
3	9.3 (40% V_I)	3	9	Trailing	17.6	79
4	6.7 (50% V_I)	1.5	5	Trailing	17.7	77
5	9.7 (50% V_I)	3	7	Leading	18.0	81
6	13.9 (50% V_I)	0	9	Leading	24.4	61
7	7.7 (60% V_I)	3	5	Leading	17.3	71
8	11.8 (60% V_I)	0	7	Trailing	20.4	76
9	16.5 (60% V_I)	1.5	9	Leading	24.5	150
Opti 1.	9.9 (50% V_I)	3	7	Trailing	18.0	57
Opti 2.	9.9 (50% V_I)	3	7	Leading	18.3	71

Appendix 5: Parameters used in the multi pass hybrid experiments with a thickness of 20 mm

Constant

Material	AISI 304LN	Filler wire	OK16.12	Laser power	3 kW
Groove	Partially grooved V	Filler wire diameter	0.8 mm	Focal point diameter	0.6 mm
Air gap	0.85 mm	Parallel root face	4 mm	Focal length	200 mm
Shielding gas	He, 16 l/min (extra nozzle) Ar, 7 l/min (MIG torch)				

F in table means the welding with filler wire

Variable

Weld	Wire feed rate [m/min]	Distance D_{LA} [mm]	Interaction point [mm]	Feed and torch angle [°]	Torch orientation	Focal point [mm]	Welding speed [m/min]	Groove angle [°]	Note
1									
I F	4.5		-2	40	Leading	-15	0.5	10	Root pass
II F	9.7		-1	40	Leading	-6	0.7	10	First filling pass
III	9.7	1		40	Trailing	-1	0.5	10	Second filling pass
IV	9.7	1		40	Trailing	0	0.5	10	Third filling pass
2A									
I F	4.5		-2	40	Leading	-15	0.5	10	Root pass
II	9.7	1		40	Trailing	-6	0.7	10	First filling pass
III	9.7	1		40	Trailing	-1	0.5	10	Second filling pass
IV	9.7	1		40	Trailing	0	0.5	10	Third filling pass
3B									
I F	4.5		-2	40	Leading	-15	0.5	8	Root pass
II F	9.0		-1	40	Trailing	-6	0.7	8	First filling pass
III	9.0	1		40	Trailing	-1	0.5	8	Second filling pass
IV	9.0	1		40	Trailing	0	0.5	8	Third filling pass
4									
I F	4.5		-2	40	Leading	-15	0.5	10	Root pass
II	9.9	3		50	Trailing	-8	0.7	10	First filling pass
III	14.5	3		50	Trailing	-1	0.7	10	Second filling pass
IV	7.9	3		50	Trailing	0	0.7	10	Third filling pass

Appendix 6: Parameters used in the multi pass hybrid experiments with a thickness of 30 mm

Constant

Material	AISI 304LN	Filler wire	OK16.12	Laser power	3 kW
Groove	Partially grooved V	Filler wire diameter	0.8 mm	Focal point diameter	0.6 mm
Air gap	0.85 mm	Parallel root face	4 mm	Focal length	200 mm
Shielding gas	He, 16 l/min (extra nozzle) Ar, 7 l/min (MIG torch)				

F in table means the welding with filler wire

Variable

Weld	Wire feed rate [m/min]	Distance D_{LA} [mm]	Inter-action point [mm]	Feed and torch angle [°]	Torch orien-tation	Focal point [mm]	Welding speed [m/min]	Groove angle [°]	Arc voltage [V]	Arc current [A]	Note
1											
I F	4.5		-2	40	Leading	-25	0.5	10			Root pass
II F	4.5		-2	40	Leading	-19	0.5	10			First filling pass
III F	5.5		-2	40	Leading	-14	0.5	10			Second filling pass
IV	12	1		50	Trailing	-6	0.5	10	25	49	Third filling pass
V	15	1		50	Trailing	0	0.5	10	24.5	64	Fourth filling pass
VI	10	1		50	Trailing	0	0.5	10	19	54	Fifth filling pass
2											
I F	4.5		-2	40	Leading	-25	0.5	8			Root pass
II F	5.0		-2	40	Leading	-19	0.5	8			First filling pass
III F	4.5		-2	40	Leading	-14	0.5	8			Second filling pass
IV	10.5	2		50	Leading	-6	0.5	8	18.5	103	Third filling pass
V	14.5	2		50	Leading	0	0.5	8	23.4	124	Fourth filling pass

continues...

3A											
I F	4.5		-2	40	Leading	-25	0.5	10			Root pass
II F	4.5		-2	40	Leading	-19	0.5	10			First filling pass
III F	5.5		-2	40	Leading	-14	0.5	10			Second filling pass
IV	12	2		50	Leading	-6	0.5	10	20.3	103	Third filling pass
V	15	2		50	Leading	0	0.5	10	23.6	94	Fourth filling pass
VI	10	2		50	Leading	0	0.5	10	19.6	78	Fifth filling pass
4											
I F	4.5		-2	40	Leading	-25	0.5	10			Root pass
II F	4.5		-2	40	Leading	-19	0.5	10			First filling pass
III	7	2		50	Leading	-13	0.5	10	17.7	48	Second filling pass
IV	8	2		50	Leading	-9	0.5	10	26.1	190	Third filling pass
V	8	2		50	Leading	-5	0.5	10	18	36	Fourth filling pass
VI	12	2		50	Leading	0	0.5	10	-	-	Fifth filling pass
5											
I F	4.5		-2	40	Leading	-25	0.5	10			Root pass
II F	4.5		-2	40	Leading	-19	0.5	10			First filling pass
III	13	2		50	Trailing	-10	0.5	10	22.4	120	Second filling pass
IV	18	2		50	Trailing	-3	0.5	10	25.7	143	Third filling pass

Appendix 7: The set-ups and cross-sections of the welds in the TAGUCHI experiments for the first filling pass with hybrid welding

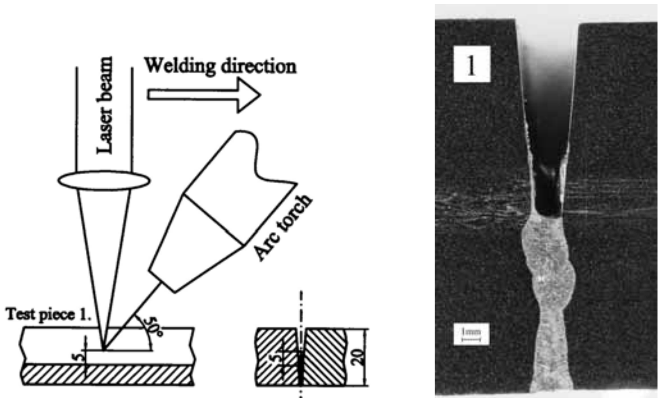

Figure A7-1. The set-up and cross-section of testpiece 1. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

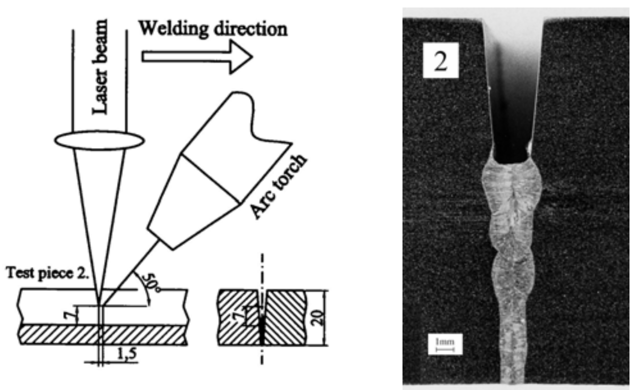

Figure A7-2. The set-up and cross-section of testpiece 2. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

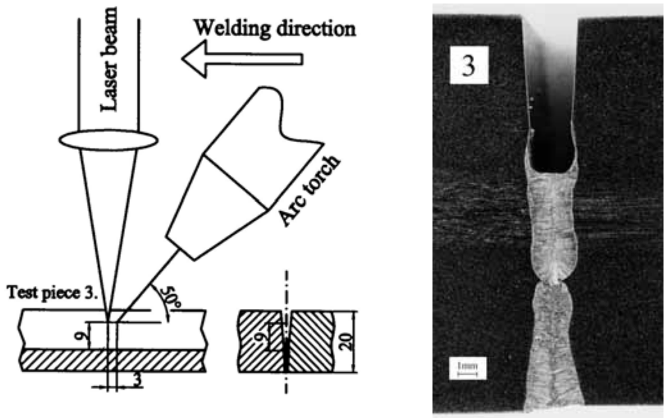

Figure A7-3. The set-up and cross-section of testpiece 3. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

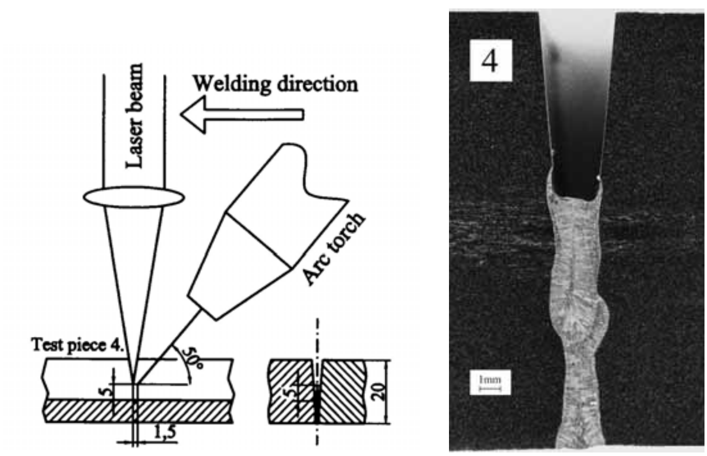

Figure A7-4. The set-up and cross-section of testpiece 4. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

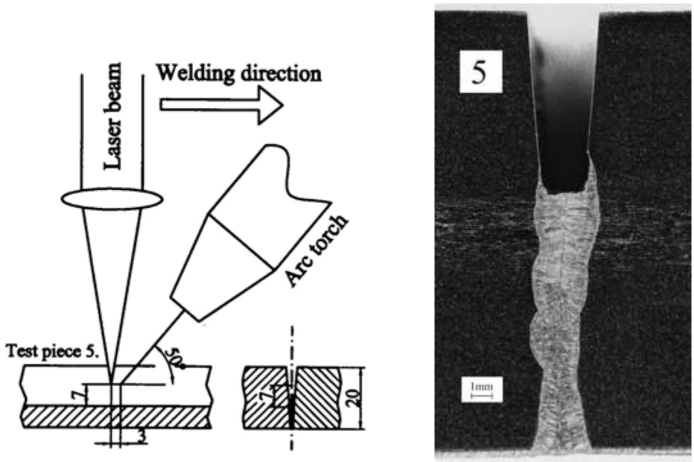

Figure A7-5. The set-up and cross-section of testpiece 5. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

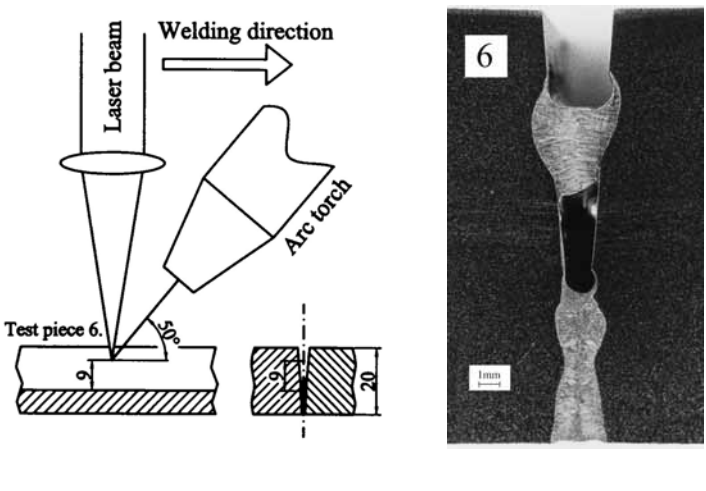

Figure A7-6. The set-up and cross-section of testpiece 6. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

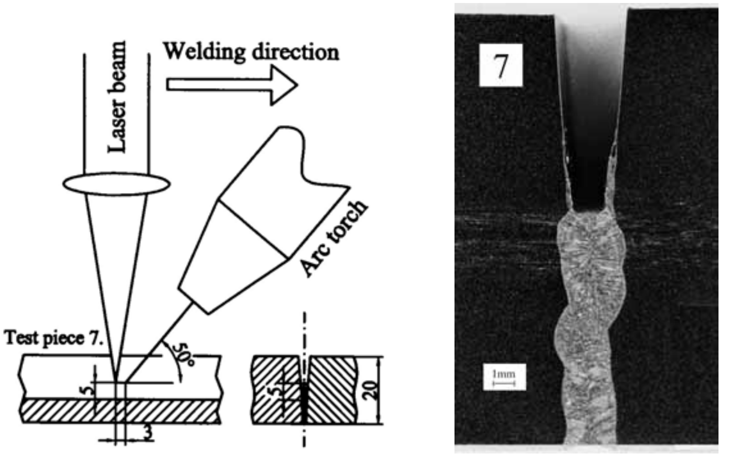

Figure A7-7. The set-up and cross-section of testpiece 7. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

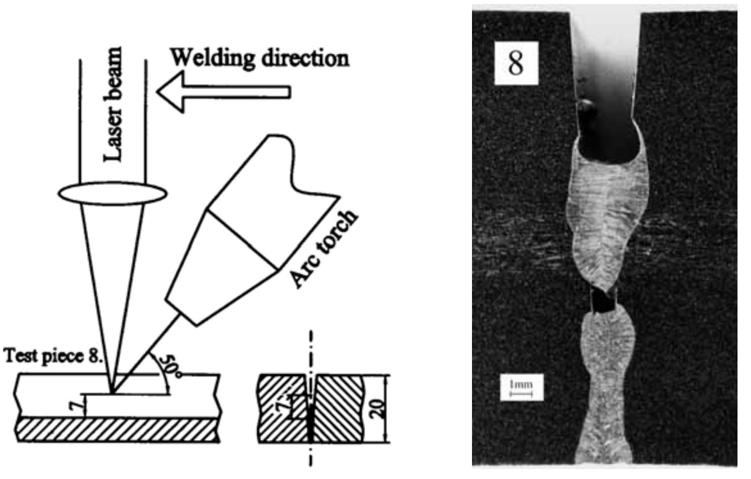

Figure A7-8. The set-up and cross-section of testpiece 8. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

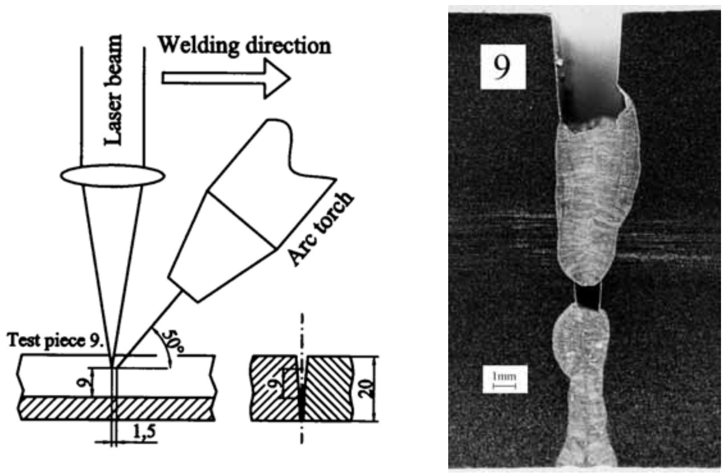

Figure A7-9. The set-up and cross-section of testpiece 9. in the TAGUCHI experiments for the first filling pass with hybrid welding. Parameters in Appendix 4.

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Novel ways of using Nd:YAG laser for welding thick section austenitic stainless steel

Abstract

Autogenous laser welding has shown many advantages over traditional welding methods in numerous applications. Still the process has disadvantages, which are impeding the applicability for the wider industrial use, e.g. tight tolerances in groove manufacturing, fixturing of the pieces against distortions and limited area of thicknesses. Owing to these limiting factors, a great deal of research work has been carried out to overcome these disadvantages by different ways.

In many studies it has been pointed out that by using filler metal with laser welding, it is possible to reduce the above-mentioned limitations. The gap bridging ability is then increased strongly and the filler wire plays an important role also when welding thicker sections by using a narrow gap joint configuration and multi pass technique. Recently so-called hybrid welding, which is a combination of the laser beam and arc welding process, has been a target of great interest. A hybrid process seems to be very effective in overcoming the reductions of autogenous laser welding. Not only for the reason of filler wire addition, but also for the extra heat coming from the arc to make the process more effective by increasing the welding speed.

In this study filler wire and an arc were used with an Nd:YAG laser in the way of a multi pass technique to weld thick austenitic stainless steel sections. To reduce the welding time and distortions, very narrow grooves were used. The applicability of the laser welding with filler wire was shown, up to a thickness of 20 mm using a 3 kW Nd:YAG laser. Hybrid welding was introduced to the narrow groove by the help of stabilizing, guiding and the contraction effect of the laser beam to the arc discharged. The applicability was shown for a groove angle of 10^{o} and thickness of up to 30 mm.

Keywords
laser welding, filler wire, hybrid welding, narrow groove, multipass, austenitic stainless steel, thesis

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