

Lasers in Manufacturing Conference 2021

High-Power Joining of Duplex Steels using Laser Beam-Submerged Arc Hybrid Welding

Rabi Lahdo^{a,*}, Sarah Nothdurft^a, Jörg Hermsdorf^a, Patrick Urbanek^b, Markus Puschmann^b, Frank Riedel^b, Ludger Overmeyer^a, Stefan Kaierle^a

^aLaser Zentrum Hannover e.V., Hollerithallee 8, Hannover 30419, Germany

^bFraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU, Reichenhainer Straße 88, Chemnitz 09126, Germany

Abstract

Duplex steels are used in many application fields due to their outstanding performance in respect to strength, toughness and corrosion resistance. These properties result from a microstructure of delta ferrite and at least 30 % of austenite. Hitherto, duplex steels are welded using multi-pass arc welding characterized by a low efficiency. Beam welding has not been successful due to the low ratio of austenite formed. Aim of this study is the development of a reliable and efficient laser beam-submerged arc hybrid welding process for duplex steel 1.4462 ($t=16$ mm) with a high proportion of austenite using a disc laser beam source ($P_L=16$ kW). The influence of the process parameters on the stability of the process are investigated by cross-section, EDX analyses and microstructure analyses. As a result, a stable and efficient one-layer hybrid process was archived. Furthermore, a higher ratio of austenite compared to laser beam welded seams forms.

Keywords: High-Power Joining; Duplex Steels; Laser Beam-Submerged Arc Hybrid Welding

1. Motivation

Duplex steels are used in many applications in which extreme requirements are placed on the material with respect to high strength and toughness combined with a high corrosion resistance. After the introduction of duplex steels into industrial use in the early 1980s, duplex steels were primarily used in applications in the oil

* Corresponding author. Tel.: +49-511-2788-358; fax: +49-511-2788-100.
E-mail address: r.lahdo@lzh.de.

and gas industry (Charles and Chemelle., 2010), whereat corrosive media are stored, transported or processed. Due to the continuous development of the duplex steels, these have subsequently also established themselves in other industries. Today, for example, these steels are used in shipbuilding for cargo tanks (Karlsson et al., 2000). Other studies show the possibility of use in steel constructions in the field of bridge construction (Sorrentino et al., 2000; Sorrentino et al. 2010). At BASF SE, one third of pressure vessels are made of austenitic and austenitic-ferritic materials (von der Hagen and Korkhaus, 2011). Due to these diverse applications, the production of duplex steels is increasing every year (Charles and Chemelle, 2010).



Fig. 1. Examples of duplex steel applications: Bridge construction (a), shipbuilding (b), transport containers (c) and tank construction (d) (TMR Stainless, 2011)

The duplex steels achieve their excellent properties through a structure consisting of 40 % delta ferrite to ensure good strength and resistance to stress corrosion cracking and 60 % austenite to ensure good corrosion resistance and toughness (Roberti et al., 1993; Mateo et al., 2001; Charles, 1995). In the welding processing of duplex steels, heat conduction has to be considered especially in order to maintain this delta ferrite austenite structure. A characteristic value for the formation of this structure is the cooling time $t_{12/8}$ due to the austenite forms predominantly in this temperature range (Folkhard, 1987; Lippold and Kotecki, 2005). On the one hand, too high cooling time $t_{12/8}$ leads to precipitations, e. g. the SIGMA-phase and CHI-phases, as well as to the formation of a brittle coarse grain zone in the delta ferrite region. Both phases reduce corrosion resistance and toughness. Furthermore, as a result of the low solubility of nitrogen in the delta ferrite chromium nitride, also a reduction of pitting resistance and toughness contributes. On the other hand, using a too low cooling time $t_{12/8}$ results in a low austenite formation in the weld, whereby the corrosion resistance is limited strongly (Lippold and Kotecki, 2005).

Duplex steels can be welded by arc welding such as tungsten inert gas welding (TIG), gas metal arc welding (GMAW) and submerged-arc welding (SAW), as well as beam welding, like electron and laser beam welding. The arc-welded joints have good mechanical-technological properties and good corrosion resistance. But these joints are characterized by a multi-layer weld, combined with complex edge preparation and a high consumption of filler material. The consequence is a high production time as well as high production costs. In addition, the high-performance arc welding processes are limited by the high heat input during welding. On the other hand, in the case of beam-welded joints, the production time and the production costs are lower, but the structure is characterized by an unfavorable delta ferrite-austenite ratio with a high a delta ferrite proportion. The consequences are reduced corrosion resistance and notch impact resistance, so that the beam welding processes could not be established in practice. Regulations such as the DVS Directive 0946 (DVS-

Richtlinie 0946, 2004) or the regulations of the Germanischer Lloyd (GL-Vorschrift, 2008) require at least 30 % austenite in the weld metal and in the heat-affected zone. The aim of these investigations is the efficient production of high-quality and single-layer welded joints with a thickness of 16 mm without significant imperfections and a suitable delta ferrite-austenite proportion by using laser beam-SA hybrid welding. In the laser beam-SA hybrid welding, the laser beam and the arc act in a common process zone or melting zone, which combines the advantages of the two welding processes. This provides a high welding speed and penetration depth, lower heat input, lower distortion, small heat affected zones and less consumption of additional materials (Lienert et al., 2011). In order to achieve the goals, systematic welding investigations are carried out at the beginning of this study to determine hybrid-specific process parameter fields, varying the geometric process parameters angles of the SA torch and the laser beam proceeding head, as well as distance between the laser beam and the SA wire electrode. Subsequently, the influence of the welding speed on the weld seam is investigated in advanced investigations.

2. State of the art

In principle, duplex steels can be joined by arc welding (GMAW, TIG, SAW, plasma welding, etc.) as well as by beam welding (laser and electron beam welding as well as hybrid welding). Generally, heat treatment must be carried out for welding processes without the use of a filler metal. This can be realised, for example, with a defocused laser beam (Kolenic et al., 2011). In this way, the cooling time can be increased in order to achieve a suitable delta ferrite-austenite structure. Thus, in (Krasnorutskiy, 2011), by using a multi-process technique in electron beam welding, the electron beam was used not only for joining but also for post heat treatment.

In (Taban and Kaluc, 2011) a comparison between laser and plasma welding without filler material is carried out on duplex steel 1.4462 and on super duplex steel 1.4410. Due to the high cooling rate and short cooling time $t_{12/8}$ of laser welding, the delta ferrite-rich samples achieve significantly lower notch impact energy. The authors refer to the possible use of a laser-GMA hybrid welding process with filler material to achieve the required duplex structure.

In (Westin, 2011), single-pass welds with a laser-MSG hybrid welding process are investigated on 13.5 mm thick duplex sheets. As a result, a clean through-weld without pores could be produced. In the root area, no austenitic microstructure is formed due to the absence of the filler material and the high cooling rate. Therefore, various thick foils of nickel were applied as filler material to the seam flanks, whereby a balanced ratio of delta ferrite and austenite could be produced.

Using the bridge construction duplex steel 1.4462 in, the SAW and laser-GMA hybrid welding processes were compared in (Sorrentino et al., 2000; Sorrentino et al. 2010). The technologies and the metallurgical properties were investigated. The investigations showed that SA single wire welding allows a safe production of welded joints with acceptable mechanical-technological properties and a good ratio of austenite and delta ferrite. In contrast, the hybrid-welded joints did not show an optimal result in terms of the microstructure.

A comparison of electron beam welded duplex steel 1.4462 ($t = 10$ mm) with and without filler material are carried out in (Steffens et al, 1993). Pure nickel and SG X2CrNiMoN G 22 9 3 N L / ER2209 were used as filler metal. It was shown that in the root of the weld, mixing of the filler material with the base material to maintain the required microstructure can only be achieved by means of beam patterns (beam deflection). Based on exposure tests in 10 % FeCl₃ solution, it was determined that corrosion begins in the delta ferrite region. The influence of the microstructure of the joining zone on the tensile strength can be estimated as low, as the samples failed exclusively in the base material.

Due to the high cooling rates in the weld metal, filler metals similar to the filler material type with an increased content of austenite-forming elements such as nitrogen are used in welding processes with filler material. In this case, the mixing between the base metal and the filler material must be kept low, as otherwise

an undesirably high austenite content will occur in the mixing zone and have a negative effect on the material properties. In this respect, investigations were carried out on TIG, GMA and SA welded duplex steel samples with regard to notch impact toughness and pitting corrosion resistance (Tösch et al., 1994).

Both solid and flux cored wires can be used for welding duplex steels. When using cored wires, however, it should be noted that it is difficult to maintain the mechanical-technological and the corrosion properties. Therefore, it is necessary to carry out an optimisation and adaptation to the corresponding welding task (Bonne, et al., 2007). In (Dhooge and Deleu, 1997), the mechanical-technological quality (tensile strength, notch impact toughness) and the microstructure of submerged-arc and GMA welded joints with solid and flux cored wires were compared. The workpiece thickness of the duplex steel 1.4462 used was 25 mm. In the MSG welds with flux cored wire, nitrides occurred in the fusion zone between the base metal and the weld metal, which can lead to a reduction in corrosion resistance. Furthermore, with an increase in grain size, delta ferrite content and amounts of nitrides, an increasing hardness was observed (Brumm, 2011).

3. Experimental setup and materials used

The investigations of laser beam-SA hybrid welding processes were carried out using a disc laser beam source TruDisk 16002 (Trumpf Laser- und Systemtechnik GmbH) with a maximum power of $P_L = 16$ kW and a welding current source ESAB LAF 1001 (ESAB Welding & Cutting GmbH) with a maximum current of $C = 1000$ A. The laser processing head BEO D70 (Trumpf Laser- und Systemtechnik GmbH) and a torch (ESAB Welding & Cutting GmbH) were fixed to the robot KUKA KR60 (KUKA AG). In order to realise a focus diameter of $d_{Focus} = 0.4$ mm a focal length of $f_f = 400$ mm, a collimation length of $f_k = 200$ mm, and a fibre diameter of $d_{fibre} = 200$ μ m were utilized. Fig 2 shows the experimental setup with the submerged-torch, the laser processing head and the workpiece.

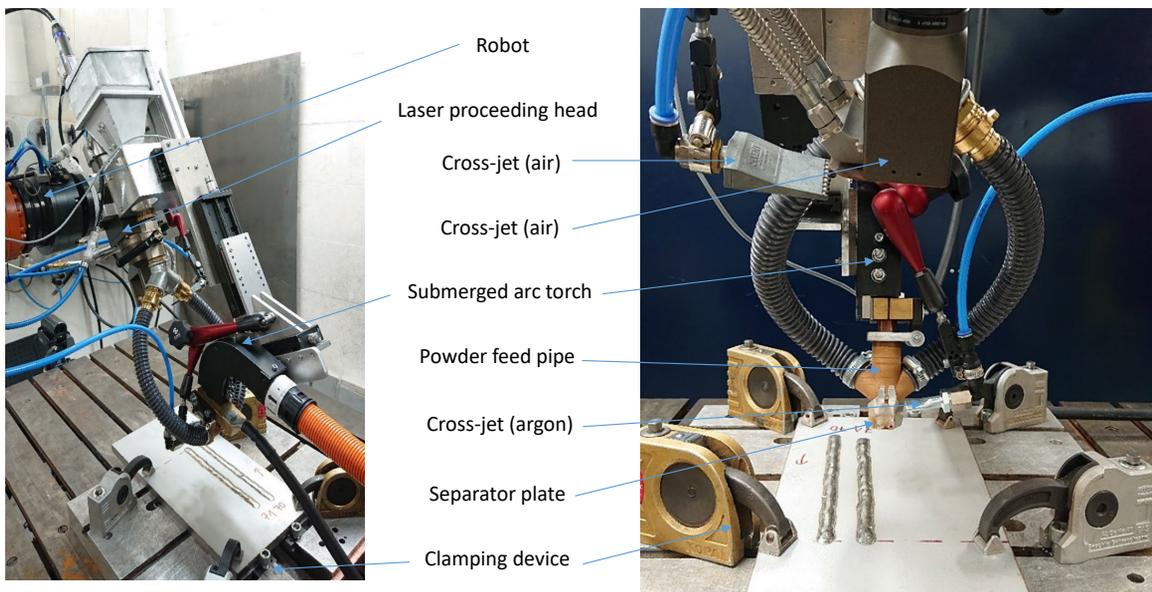


Fig. 2. Experimental setup for laser beam-SA hybrid welding

For the process development the duplex steel 1.4462 (Outokumpu Nirosta GmbH) with a thickness of 16 mm was used. The samples have a length of 400 mm and a width of 100 mm. The duplex steel used is a rust and acid resistant austenitic-ferritic chromium-nickel-molybdenum steel. Table 1 shows the chemical composition of the duplex steel. A filler wire S 22 9 3 N L / ER2209 with a diameter of 2.4 mm in combination with neutral Fluoride-basic SAW-flux (10.93) were used. In Table 2 the chemical composition of the filler wire is illustrated.

Table 1. Chemical composition of the duplex steel 1.4462 ($t = 16$ mm)

1.4462	C	Si	Mn	P	S	Cr	Mo	Ni	N
[%]	0,03	1,00	2,00	0,035	0,02	23,00	3,50	6,50	0,22

Table 2. Chemical composition of filler wire S 22 9 3 N L / ER2209

S 22 9 3 N L / ER2209	Cr	Mo	Ni	N
[%]	23,00	3,00	9,00	0,15

4. Experimental procedure and evaluation

At the beginning of the process development, fundamental investigations on laser beam-SA hybrid welding are carried out to determine the influence of geometric process parameters on the formation of laser beam-SA hybrid welding process. This includes parameters such as the distance between wire and laser beam a and the angle of the laser proceeding head α and the SA torch β . In particular, it is investigated with which geometrical process parameters a hybrid welding process and not a process combination results under variation of the seam preparation geometry (I-seam and Y-seam) with a bevel height of 5.0 mm and 7.5 mm with an opening angle of 30°. Table 3 shows the experimental matrix with 81 possible parameter combinations and in Table 4 the constant parameters used.

Table 3: Experimental matrix with 81 possible parameter combinations for the fundamental investigations

Parameter	Variation		
	Seam preparation geometry	I-seam	30°Y5 mm
Distance between wire and laser beam a (mm)	16	18	20
Angle of laser proceeding head α (°)	0	15	30
Angle of SA torch β (°)	0	10	15

Table 4: Constant parameters during welding process development

Laser beam power P_L (kW)	5 – 8
Operating mode	Continuous wave
Welding speed v_w (m/min)	1.0
Focus position Δz (mm)	-4
Welding current C (A)	500
Welding voltage V_{Vol} (V)	30
Control modus (-)	CA
Stickout length s (mm)	20
Free wire end (mm)	3

Subsequently, the influence of the welding speed is examined within the advanced investigations on the Y-seam with a bevel height of 5 mm with a parameter combination from the resulting hybrid welding field. In this context, the effect of welding speed on the weld seam geometry, weld seam imperfections and the microstructure is investigated. To determine the weld seam geometry and weld seam imperfections, the cross-sections are etched using V2A etching for a time of 1 min. For the microstructure analysis, Murakami etching with a time of 1 min is used. Using this etchant, ferritic and austenitic microstructures can be differentiated. The ferritic part of the structure is attacked by the etchant and appears dark. The austenite grain is shown in white. To determine the penetration depth of the filler metal, energy dispersive X-ray (EDX) line scans are performed on the cross-sections along the vertical center line of the weld metal. The penetration depth of the filler material is determined by detecting nickel, as this element shows a high difference of 2.5 % between the base material and the filler metal.

5. Results and discussions

5.1. Fundamental investigations

5.1.1. Determination of process parameter fields for laser beam-SA hybrid welding

For the realisation of a welding process coupling (hybrid welding), process parameter fields were systematically investigated by means of experimental matrix. The results of the welding process development on I-seams show that the smallest distance a and the maximum angles α and β are necessary to achieve a hybrid welding process. Increasing the distance a and decreasing the angle of the laser proceeding head α as well as the angle of the SA torch β lead to the formation of two separate melt pools and thus no hybrid welding process is present. Only the parameter combination of $a = 16$ mm, $\alpha = 30^\circ$ and $\beta = 15^\circ$ enables a laser beam-SA hybrid welding process, see Fig 3 (a). The laser beam power for the experiments was $P_L = 8$ kW.

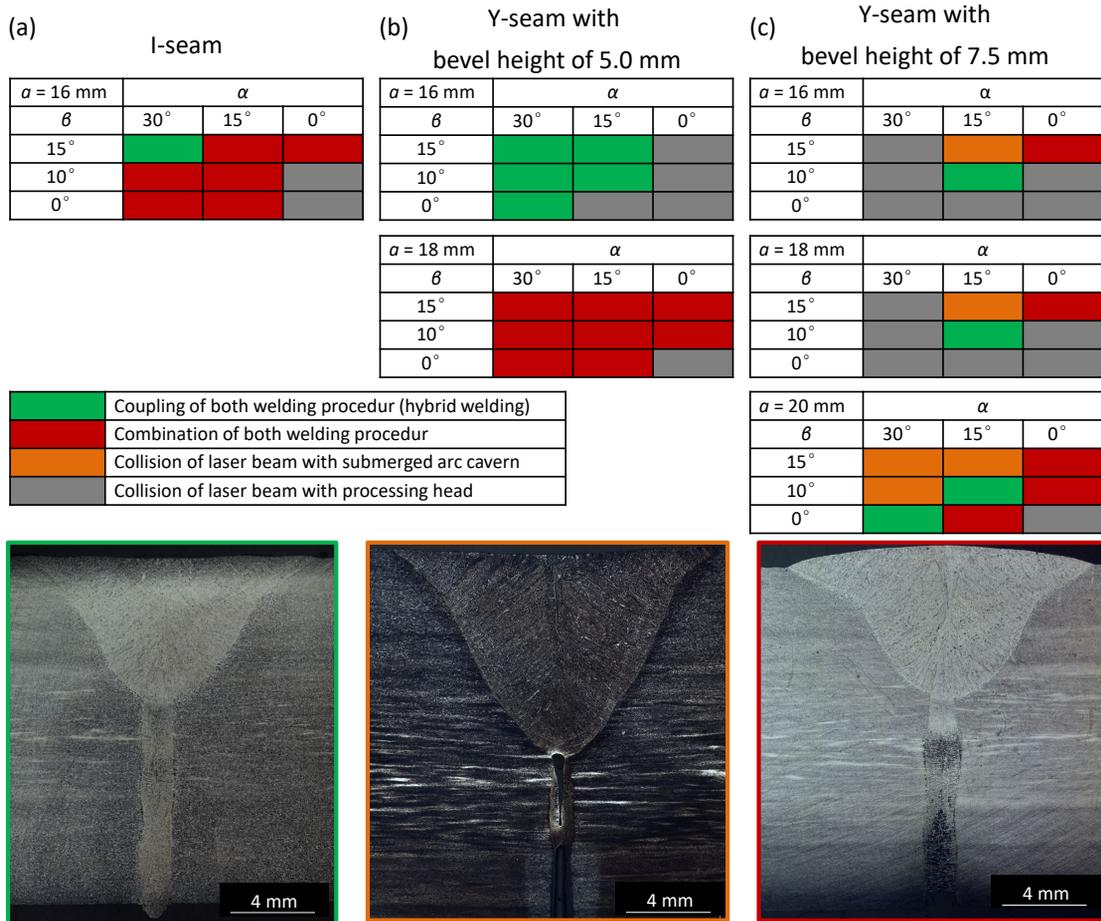


Fig. 3. Process parameter fields for laser beam-SA hybrid welding as a function of the geometric process parameters and the seam preparation geometry: (a) I-seam, (b) Y-seam with bevel height of 5.0 mm and (c) Y-seam with bevel height of 7.5 mm, each with a total opening angle of 30°

For the process development on the Y-seam with a bevel height of 5 mm, the laser beam power was adjusted to $P_L = 6 \text{ kW}$. Compared to the I-seam, five parameter combinations result for the laser beam-SA hybrid welding of the Y-seam at a distance of 16 mm with otherwise unchanged parameters, see Fig 3 (b). Accordingly, hybrid welding processes (green fields of the experimental matrix) are possible with parameter combinations from $\alpha = 15^\circ$ and $\beta = 10^\circ$ up to $\alpha = 30^\circ$ and $\beta = 15^\circ$. Combinations with smaller angles, on the other hand, cannot be implemented because the wire deflector of the submerged-arc torch or the aluminium separator plate collide with the laser beam (grey fields of the experimental matrix). Increasing the distance by 2 mm to $a = 18 \text{ mm}$ means that no hybrid welding processes are achieved despite a bevel height of 5 mm.

With the Y-seam preparation with a bevel height of 7.5 mm, hybrid welding is achievable up to a distance $a = 20 \text{ mm}$, see Fig 3 (c). The laser beam power was adjusted to $P_L = 5 \text{ kW}$. Increasing the bevel height to 7.5 mm enables further a reduction of the distance between the laser beam and the submerged-arc wire in the bevel root. The distance a measured in relation to the sheet surface can thus be further increased without separating the melt pools. The parameter field for successful laser beam-SA hybrid welding processes grows

as a result. At the same time, however, distances of $a = 16$ mm and $a = 18$ mm result in a larger number of parameter combinations that cannot be implemented or investigated (grey fields of the experimental matrix) to protect the processing head. The point of impact of the laser beam moves too far below the aluminium separator plate in the root of the bevel, so that the separator plate and the powder feed pipe can be damaged by the rising vapour plume. At the same time, it can be observed that the distance is too small for a defect-free welding process (orange fields of the experimental matrix). These welds are feasible with the experimental set-up, but due to the small distance a , the laser beam couples into the SA weld pool or into the SA cavern immediately after hitting the bevel (orange fields of the experimental matrix). As a result, the welding process becomes unstable and a significantly lower penetration depth is achieved because the laser beam is absorbed by the cavern.

5.2. Advanced investigations

For the further investigations, the welding parameter combination $\alpha = 30^\circ$, $\beta = 0^\circ$ and $P_L = 6$ kW for the Y-seam with a bevel high of 5 mm is selected as an example in order to investigate the influence of the welding speed on the welded seams regarding the weld seam geometry (section 5.2.1), penetration depth of the filler material (section 5.2.2) and the austenite ratio (section 5.2.3). The welding speed v_w was varied from 0.6 m/min and 1.0 m/min up to 1.4 m/min.

5.2.1. Metallographic analyses - Cross-section

As the welding speed increases, the seam width, the seam root width and the depth of the SA-dominated area increases due to higher energy per unit length or heat input, respectively. Fig. 4 shows cross-sections under variation of the welding speed for a Y-seam with a bevel height of 5 mm. Based on the cross-sections, the SA-dominated area increase from 5.1 mm at a welding speed of $v_w = 1.4$ m/min to 8.2 mm at welding a speed of $v_w = 0.6$ m/min. Furthermore, at welding speeds of v_w of 0.6 m/min to 1.0 m/min, hybrid welds are produced without imperfections. A further increase of the welding speed to $v_w = 1.4$ m/min, can lead to weld imperfections in form of lack of side fusion in the transition area between the heat-affected zone or fusion line and the weld metal as well as cavity between the transition area between the submerged-arc-dominated and the laser-beam-dominated area. At such a high welding speed, the energy per unit length is not sufficient to melt the flanks reliably. The formation of cavities can be explained by the fact that the molten pools resulting from SA and laser beam welding do not combine due to the low energy per unit length.

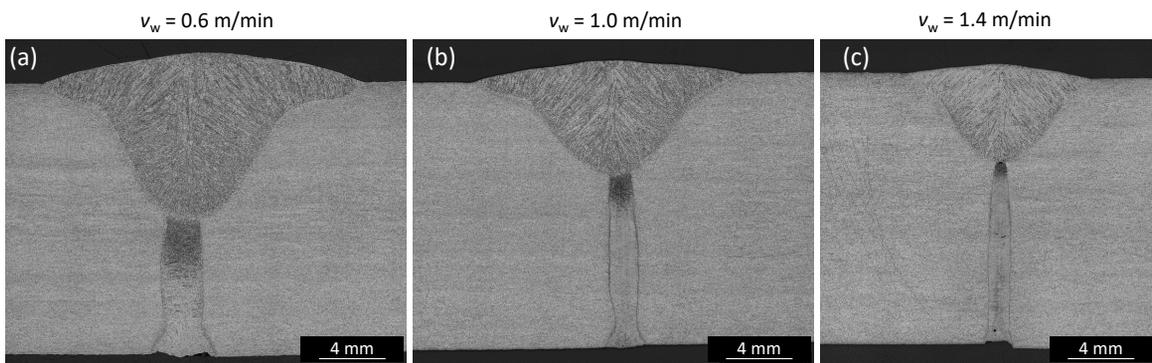


Fig. 4. Cross-sections of hybrid seams at a welding speed v_w of 0.6 m/min (a), 1.0 m/min (b) and 1.4 m/min (c) for Y-seam with bevel height of 5 mm

5.2.2. Investigation of the penetration depth of the filler material

The chemical analysis of the hybrid welds shows that the filler metal, in the form of nickel content, is detectable below the SA-dominated region. Fig. 5 shows the result of the EDX analyses for Y-seam with a bevel height of 5 mm under variation of the welding speed. According to this, the penetration depth of the filler material depends strongly on the welding speed or on the energy per unit length, respectively. Basically, the penetration depth of the filler material increases with increasing energy per unit length. Since an increasing energy per unit length leads to an increase in the liquid time during welding, the filler material is given more time to mix better with the area melted by the laser beam. The averaged nickel content in this area is about 8.5 % and below the penetration depth of the SA about 6.5 %. This means that the percentage content is about 2 % higher as that of the base metal. For example, at a welding speed of $v_w = 0.6$ m/min a penetration depth of about 10 mm and at a welding speed of $v_w = 1.4$ m/min a penetration depth of about 6 mm is achieved. Using the highest welding speed, it was not possible to connect the two molten pools in some cross-sections due to the insufficient energy per unit length, which consequently limits the penetration depth of the filler material in the SA-dominated area. In these cross-sections, as already explained in the previous chapter, a cavity was observed in the transition area. The extent to which the penetration depth of the filler material affects the microstructure ratio will be considered in the next chapter.

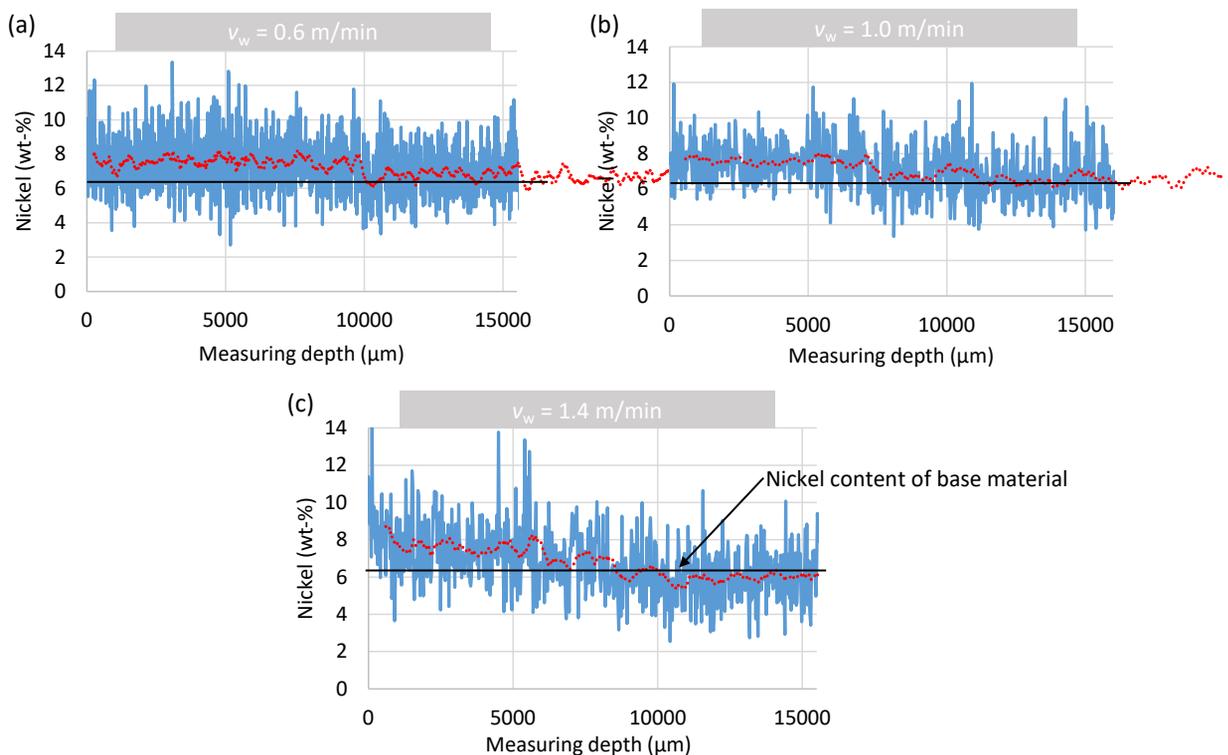


Fig. 5. Nickel content over the welding depth in the weld metal measured at Y-seam with a bevel height of 5 mm and a welding speed v_w of 0.6 m/min (a), 1.0 m/min (b) and 1.4 m/min (c); black line: nickel content of base material

5.2.3. Determination of the delta ferrite-austenite proportion

In order to achieve the required properties of the duplex steel, a minimum proportion of austenite of 30 % in the weld must be ensured. In order to investigate the influence of the filler material on the austenite content, the austenite content along the vertical centre line of the weld metal at Y-seam with bevel height of 5 mm under variation of the welding speed v_w of 0.6 /min, 1.0 m/min and 1.4 m/min was shown in Fig. 6 (a). Fig. 6 (b) shows the averaged austenite content as a function of the welding speed, taking the penetration depth of the filler material into account.

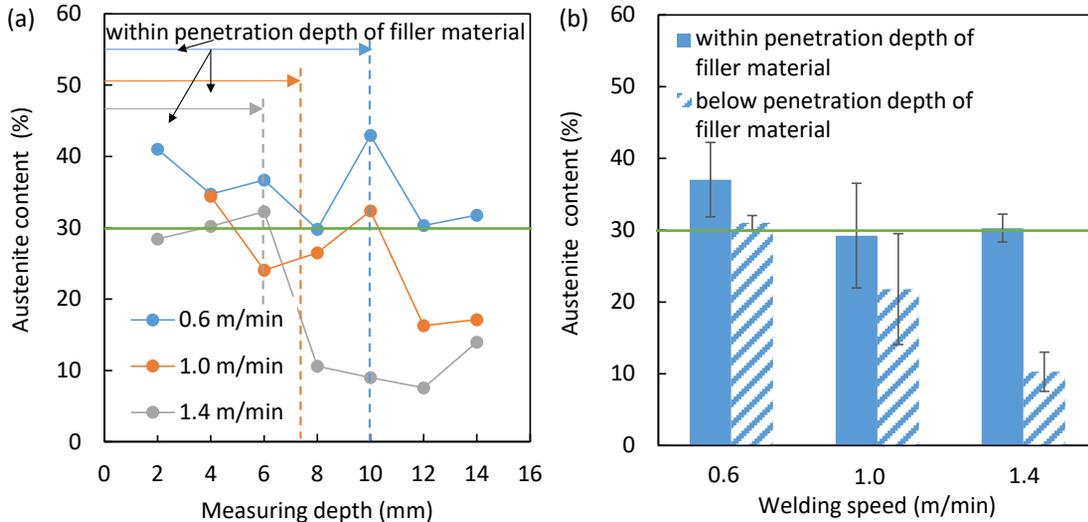


Fig. 6. Austenite content measured over the weld penetration depth for a Y-seam with bevel height of 5 mm and a welding speed v_w of 0.6 m/min and 1.4 m/min (a) and averaged austenite content taking into account the penetration depth of the filler material (b)

The austenite content within the penetration depth of the filler material is comparatively higher than below its penetration depth. This can be explained by the fact that the filler material has a higher proportion of austenite-forming nickel compared to the base material. On the other hand, the penetration depth range of the filler material is largely characterized by the SA-dominated area, which is characterized by a lower cooling rate and longer cooling time $t_{12/8}$ compared to the laser-dominated range. In correlation with the chemical composition (section 5.2.2) in relation to the penetration depth of the filler material, a leak in the course of the austenite content can be observed. Such a correlation was already found in (Westin et al., 2011). The higher the welding speed, the more pronounced the difference. Here, an increasing welding speed leads to a decrease of the austenite content due to an increasing cooling rate, especially in the area below the penetration depth of the filler metal. The austenite is not given sufficient time to form in the weld. At a low welding speed v_w of 0.6 m/min, an averaged austenite content of at least 30 % can be seen even below the penetration depth of the filler metal. Autogenous laser beam welding with comparable welding speed results in an austenite content of about 13 %. In view of this finding, it can be concluded that laser beam-SA hybrid welding at low welding speed leads to an extension of the cooling time and thus also to a higher austenite content. Using higher welding speeds, the required austenite content of at least 30 % below the penetration depth of the filler material cannot be met.

6. Conclusions

In order to increase the welding productivity of duplex steels, efficient single-layer laser beam-SA hybrid welding processes were to be developed in these investigations with the aim of achieving a minimum austenite content of 30 % and weld seams without imperfections. The process development was carried out on duplex steel 1.4462 with a plate thickness of 16 mm. In addition, the study is divided into fundamental and advanced welding investigations. Within the scope of the basic welding investigations, the influence of geometric process parameters, such as the distance between the SA wire electrode and the laser beam as well as the angle of the SA torch and the laser beam, on hybrid welding was analysed with the help of an experimental matrix. Subsequently, the influence of the welding speed on the weld seam with regard to the weld seam geometry, the weld seam imperfections, the penetration depth of the filler material and the austenite-ferrite microstructure ratio was investigated in the advanced investigations.

In the basic investigations, it was shown that the geometric parameters and the seam preparation geometry have a high influence on hybrid welding. Depending on the setting, a welding combination or hybrid welding results. The distance between the SA arc torch and the laser beam as well as the seam preparation geometry have the largest influence. A too high distance leads to a weld combination and a too low distance to the laser beam coupling into the arc cavern leads to a noticeable decrease of the penetration depth. Furthermore, with increasing bevel heights, a larger number of parameter combinations for hybrid welding is possible.

In the course of further investigations, hybrid welds with a Y-seam preparation and bevel heights of 5 mm were produced without imperfections, taking the welding speed into account. The generated cross-sections of the hybrid welds show the required ferrite-austenite ratio of at least 30 % at a low welding speed of 0.6 m/min. The process development also shows that the joining of 16 mm thick sheets can be carried out on one side and in a single layer using laser beam-SA hybrid welding. The laser beam-SA hybrid welding thus not only enables the saving of a heat treatment, but also a considerable reduction of welding times due to the necessity of only one layer. This can lead to reduced cycle times and cost savings in many industrial applications. In addition, it is shown how effectively laser beam-SA hybrid welding can be used and how an efficient hybrid welding process has been created by linking two conventional welding processes.

As outlook, further investigations will be carried out with a laser beam that is wobbling transversal to the welding direction to increase the penetration depth of the filler material and using laser beam powers of up to $P_L = 16$ kW to increase the energy per unit length at high welding speeds.

Acknowledgements

The research project IFG 20736 BG / P 1227 "Joining of Duplex Stainless Steels using the Laser- submerged arc hybrid welding" from the Research Association for steel Application (FOSTA), Düsseldorf, is supported by the Federal Ministry of Economic Affairs and Energy through the German Federation of Industrial Research Associations (AiF) as part of the programme for promoting industrial cooperative research (IGF) on the basis of a decision by the German Bundestag. The project is carried out at Laser Zentrum Hannover e.V. and Fraunhofer Institute for Machine Tools and Forming Technology IWU.

References

Bonnel, J.-M., Pease, N.C., Cordari, A., 2007. Duplex and superduplex cored wires: Modern consumables for modern steel; Duplex 2007 International Conference and Expo, Grado.

- Brumm, S., 2011. Schweißseignung des Duplex-Stahls 1.4462 mit dem UP-Schweißverfahren - Problemstellungen und Lösungswege; DVS Berichte Band 270, DVS-Verlag, Düsseldorf.
- Charles, J., 1995. Composition and properties of duplex stainless steels, *Weld. World (UK)* 36, pp. 43-55.
- Charles, J., Chemelle, P., 2010. The history of duplex developments, nowadays DSS properties and duplex market future trends; 8. Duplex stainless Steels conference, Beaune.
- Dhooge, A., Deleu, E., 1997. Low temperature fracture toughness of thick duplex and superduplex stainless steel weldments; *Welding in the world* 39, pp. 47 - 52, Gent.
- DVS-Richtlinie 0946, 2004. Empfehlungen zum Schweißen von nicht rostenden austenitisch-ferritischen Duplex- und Superduplexstählen.
- Folkhard, E., 1987. *Welding Metallurgy of Stainless Steels*, Springer-Verlag, Wien - New York, p. 186.
- GL-Vorschrift, 2008. Schweißen von schiffbaulichen Konstruktionen II-Teil 3.
- Karlsson, L., Strömberg, J., Rigdal, S., Lake, F., 2000. Developments in welding of duplex stainless cargo tanks for chemical carriers; *Duplex America 2000*, pp. 273 - 280, Houston.
- Kolenic, F., Kovac, L., Drimeal, D., 2011. Effect of laser welding conditions on austenite/ferrite ratio in duplex stainless steel 2507 welds, *Welding in the world* 55, pp. 19 - 25, Bratislava.
- Krasnorutskiy, S., 2011. Metallkundlich-technologische Untersuchungen zum Elektronenstrahlschweißen von Duplexstahl ohne Schweißzusatz, *DVS Berichte Band 270*, pp. 17 - 22, DVS-Verlag, Düsseldorf.
- Lienert, T., Siewert, T., Babu, S., Acoff, V., 2011. Hybrid Laser Arc Welding, *ASM Handbook 6A, Welding Fundamentals and Processes*, p. 32.
- Lippold, J.C., Kotecki, D.J., 2005. *Welding Metallurgy and Weldability of Stainless Steels*, John Wiley & Sons, Hoboken, p. 238, New Jersey.
- Mateo, A., Llanes, L., Akdut, N., Anglada, M., 2001. High cycle fatigue behaviour of a standard duplex stainless steel plate and bar, *Mater. Sci. Eng. A*, pp. 319 - 321.
- Roberti, R., Nicodemi, W., La Vecchia, G.M., Basha, Sh., 1993. J-R curve dependence on specimen geometry and microstructure in two austenitic-ferritic stainless steels, *Int. J. Pres. Ves. & Piping* 55, pp. 343 -352.
- Sorrentino, S., Fersini, M., Zilli, G., 2009. Comparison between SAW and laser welding processes applied to duplex structures for bridges, *Welding International*, pp. 687 - 698, Roma.
- Sorrentino, S., Fersini, M., Zilli, G., 2010. Duplex stainless steel for bridges construction: comparison between saw and laser-gma hybrid welding, *Welding in the World Vol. 54*, pp. R123 - R133, Roma.
- Steffens, H.-D., Hartung, F., Buchmann, Ch., 1993. Elektronenstrahlschweißen des Duplexstahls X 2 CrNiMoN 22 5 3, *DVS Bereiche Band 155*, pp. 81 - 85, DVS Verlag, Düsseldorf.
- Taban, E., Kaluc, E., 2011. Welding behaviour of duplex and superduplex stainless steels using laser and plasma arc welding processes, *Welding in the World Vol. 55*, pp. 48 - 57, Kocaeli.
- Tösch, J., Rabensteiner, G., Adam, W., 1994. Einfluss der Schweißverfahren auf die Eigenschaften von Schweißverbindungen an Duplex-Stählen, *DVS Berichte Band 162*, DVS-Verlag, Düsseldorf.
- von der Hagen, J., Korkhaus, J., 2011. Chemieapparate aus hochlegierten Stählen - Schweißnähte als Angriffspunkt der Korrosion, *DVS Berichte Band 274*, DVS-Verlag, Düsseldorf.
- Westin, E.M., Stelling, K., Gumenyuk, A., 2011. Single-pass laser-gma hybrid welding of 13.5 mm thick duplex stainless steel, *Welding in the world Vol. 55*, pp. 39 - 49, Berlin.