Laser Hybrid Welding of High Strength Steels

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Abstract

This paper presents results from an ongoing investigation into laser–arc-hybrid welding of thick high strength steels used in the heavy mechanical and heavy automotive industries. The results include welding parameters for a 6 and 12 kW laser combined with conventional MIG/MAG equipment.

In this work, the laser–arc-hybrid welding technique has been further developed and applied to thick steel plate welding, giving high quality welds at high speeds. Successful welds were obtained on 6-12 mm plate thickness with laser, plasma or sheared edges as received from the blanking process. Thereby any costly, additional joint preparation is avoided, giving the hybrid welding technique an enhanced potential for use in the heavy automotive and mechanical industries.

1. Introduction

High power laser beam welding is today an industrial joining process used in competition with conventional arc-welding processes. Both types of processes have their own characteristics, advantages and disadvantages. The main advantages of the laser welding process are low heat input and high welding speed typically producing a narrow and deep melt profile. However, the process is sensitive to joint gaps giving undercuts, which normally not are acceptable. Joint gaps of any kind may also influence the formation of solidification flaws when butt welding steels thicker than approximately 10 mm due to lack of material in the weld metal during the solidification phase of the welding process [1]. The arc welding processes have high heat input, and are typically conduction-limited processes producing wider and shallower welds at relatively low welding speeds. However, the arc welding processes are very efficient regarding the addition of filler material and therefore preferred when larger joint gaps are present.

In order to overcome the disadvantages of the laser and the conventional arc welding methods, these may be combined in such a way that the processes interact to form a new welding process; the laser-arc-hybrid welding process (LAH). The fundamentals of this process have been presented in a number of papers, e.g. [2-7], which show that the LAH-process offers substantial advantages including reduced total heat input, higher welding speeds, increased arc (process) stability and a substantial gap bridging ability.

Much of the previous work has been focused on welding different types of V-joints, where the LAH-process shows excellent welding results. However, the preparation of V-joints are time consuming and costly, which is why this method is not preferred by industry in general. Industrial users prefer to weld material without any additional joint preparation, which means the joints normally should be laser, gas, plasma, or mechanically (sheared) cut. This also means that oxides, burrs etc may be present in the joint.

This work has therefore been directed towards exploring the LAH process when welding thick structural steels under industrial conditions, i.e. using sheets as received from the industrial blanking process. The main objective has been to learn the fundamentals of the laser arc hybrid welding for laser, plasma or mechanically cut, 6-12 mm, thick sheet metal. The LAH process will also be demonstrated in selected industrial applications but this work will be reported later.

2. Experimental setup

A 6 kW CO_2-laser was used together with conventional welding equipment consisting of a welding rectifier model ESAB Aristo LUD450W. This was provided with a MIG/MAG wire feed unit model ESAB A10 MEK 44C. The welding gun was connected close to the laser focusing optic at an angle of about 45?, and is adjustable by three micrometer screws to allow an accurate setting in all directions, figure 2.1. Also a 17 kW CO_2- laser, was used at 12 kW power level. The angle between the gun and the work piece surface was 67 °in this case. The other parameters concerning the experimental set up are shown in table 2.1. The principles and some definitions of the LAH-process are also shown in figure 2.1.

As described in the literature the LAH-process is complex as two processes are combined. In many papers no specific information is presented on the parameters used, only their

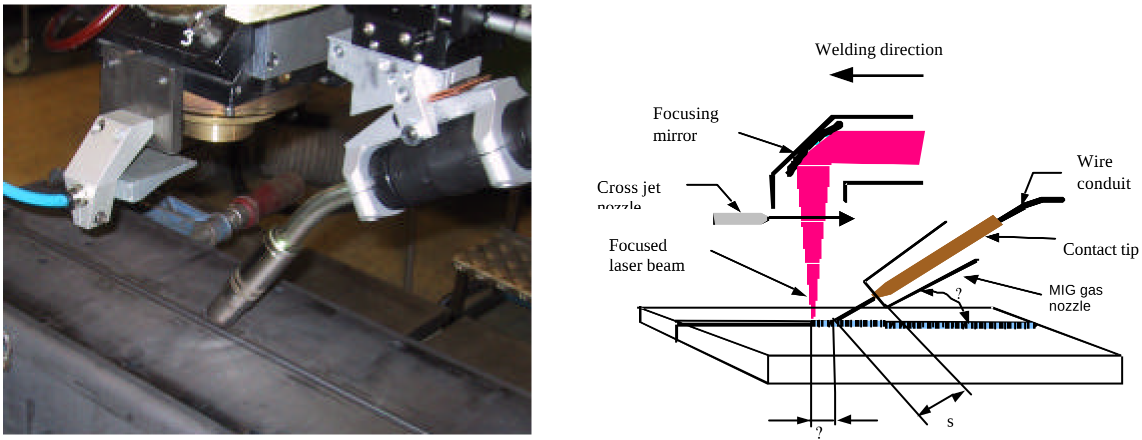


Figure 2.1. Experimental set-up for 6 kW laser and the principles and definitions of the LAH-process.

importance is highlighted. Such parameters are the position of the welding gun particularly the distance (?) between the laser beam and the wire, figure 2.1, and the angle (a) between the surface and the welding gun. Also the stick-out (s), the arc-parameters (voltage; current), welding direction and the shielding gas are of great importance.

Welding tests were done using I-, V- and sheared joints for 6, 8, 10 and 12 mm thick plates 200x100 mm in dimension. The range of parameters used is showed in table 2.1. The shielding gas used was different mixtures of helium, argon and carbon dioxide or oxygen. The flow rate was set in the range 15-30 l/min and normally the shielding gas was supplied through the MIG gas nozzle only. Normally the wire feed direction was the same as the welding direction, figure 2.1.

Table 2.1 Range of welding parameters

	6 kW CO_2-Laser	12 kW CO_2-laser
Laser power[1] [kW]	5,2	11,4
Focal length [mm]	270	300
Focus diameter [mm]	0,5	0,8
Welding speed [m/min]	0.8 – 1.7	1,1 - 2,0
Wire type and dimension [mm]	Esab OK Autrod 12.51[2] ? 0.8 , 1.0	Esab OK Autrod 12.51[2], ? 1.0
Wire feed rate [m/min]	2 - 22	9 - 15
MIG voltage [V]	15 – 32	23 - 33
MIG current [A]	30 – 242	168 - 336
Stick-out (s) [mm]	13-18	13
Distance wire laser beam (?) [mm]	1 – 4	2
Shielding gas type	Mixture of Ar, He, CO_2 or O_2	Mixture of Ar, He, CO_2 or O_2

[1)] Measured at the workpiece [2)] 0,8C, 0,9Si, 1,5Mn

The materials used were DOMEX 390XP, a high strength cold forming steel; WELDOX 960, a high strength structural steel and S355J2G3 a well known mild steel. Table 2.2 shows the composition of the welded steels.

Table 2.2 Chemical composition of welded steels.

Steel grade	C	Si	Mn	P	S	Cr	Cu	Ni	Mo	Al	Nb	V	CE_{IIW}[1)]
DOMEX 390XP, 10 mm	0.056	0.01	0.61	0.006	0.003	0.03-	0.01	0.04-	0.02	0.05	0.022	0.005	0.17
DOMEX 390XP, 12 mm	0.067	0.02	0.58	0.008	0.003	0.03	0.01	0.05	0.02	0.04	0.031	0.005	0.18
S355J2G3, 8mm[2]	0.159	0.33	1.39	0.015	0.009	0.06	0.06	0.02	0.01	0.03	--	0.004	0.27
WELDOX 960, 6, 12 mm	0.169	0.20	1.24	0.009	0.002	0.18	0.02	0.057	0.65	0.061	0.024	0.018	0.55

[1)] Carbon equivalent $CE_{IIW}(\%) = C + Mn/6 + (Cr+Mo+V)/5 + (Cu+Ni)/15$
[2)] equal to SS 2132

The joint preparations used were sheared, laser cut and milled V-joints for Domex 390XP; sheared and laser cut for S355J2G3 and plasma cut for Weldox 960.

3. Results

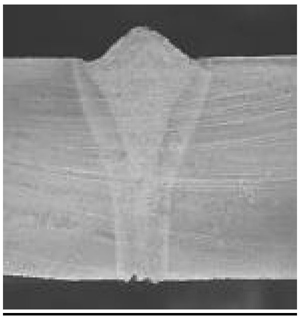
3.1 Weld appearance and strength

Weld appearance

LAH-welds in thick plates, 6-12 mm, can be produced using a wide range of processing parameters such as different process gases, laser powers, welding speeds and MIG/MAG-parameters, figure 3.1.1-3.1.5.

The weld appearance differs due to influence of the parameter combinations used. The most commonly geometric imperfections (named in ISO 6520-1), which may arise, are excessive weld reinforcement, undercut, spatter and excessive and irregular penetration or melt through. Spatter can be eliminated by relevant choice of MIG/MAG-parameters.

Use of Helium solely, or as the dominant part of the process gas mixture, tends to increse the weld reinforcement and accentuate formation of undercuts. Increased amount of Argon and CO_2 or O_2 on the other hand tends to flatten the weld reinforcement, but may in some cases also prevent full joint penetration. In steel plate thickness = 10 mm undercuts are more frequently observed.



Figur 3.1.1. DOMEX 390 XP, 8mm, milled edges, 100He v=1,3 m/min, wire ø 0,8 mm, wire feed=10 m/min, P_L=5,2 kW, P_{MIG}= 3,7 kW (spec HH6)

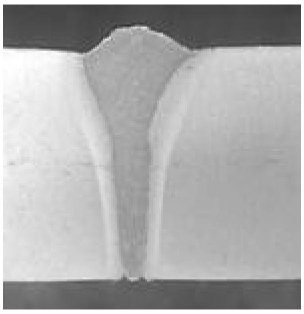


Figure 3.1.2. DOMEX 390 XP, 8mm, sheared edges, He/Ar/CO_2, v=1,3 m/min, wire ø 0,8 mm, wire feed=8m/min, P_L=5,2 kW, P_{MIG}= 3,8 kW (spec.HK10)

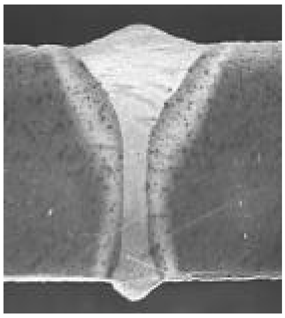


Figure 3.1.5. DOMEX 390 XP 8mm, laser cut edges, He/Ar/CO_2, v=1,8 m/min, wire ø1,0 mm, wire feed =14m/min, P_L=11,4 kW, P_{MIG}= 3,8 kW (spec.FA9)

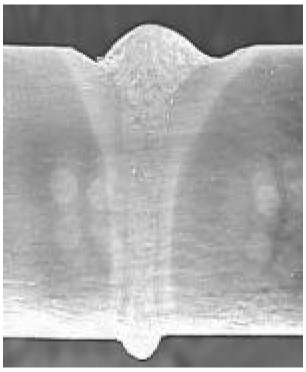


Figure 3.1.3. DOMEX 390XP 10mm, laser cut edges, He/Ar/CO_2, v=1,6 m/min, wire ø1,0 mm, wire feed=10,7m/min, P_L=5,2 kW, P_{MIG}= 3,7 kW, (spec. FB23)

Figure 3.1.4.~~,~~ DOMEX 390XP 12mm, laser cut edges, He/Ar, v=1,2 m/min, wire ø1,0 mm, wire feed=8,8m/min, P_L=5,2 kW, P_{MIG}= 3,7 kW, (spec. FC2)

The joint preparation will also influence the weld geometry and quality. Slightly V-formed metal clean, edges as received from milling or shearing operations could normally be LAH-welded with good results. Oxide layers (will be discussed later under section 3.3) formed during laser- or plasma cutting, on plate thickness = 10 mm, will often cause excessive and irregular penetration and deeper undercuts. However good results can be obtained with residual oxide layers on 8 mm plates (figures 3.1.5 and 3.2.1). With regard to weld geometry, approved welding results, according to highest standard welding classes (EN ISO 13919-1), can be obtained in most cases regardless of observed minor undercuts.

Weld strength

The mechanical strength of LAH-welded DOMEX 390XP and S355J2G3 has to date been examined by tensile tests and the results show that failure occurs in the base material in all tests. Also the bending tests of welded specimens are approved, giving bending properties as required for the substrate material.

3.2 Joint types and preparation

Conventional laser butt-welding requires joints of high quality, i.e. joints with small or zero gaps with smooth surfaces. This is often in opposition to industrial requirements of fast and cheap joint preparation. The most favourable case is of course no joint preparation at all, which means that the welding is done directly on the sheets as received from the blanking process. The most used blanking processes for sheet thickness larger than 5 mm are laser-, gas-, or plasma cutting as well as shearing. Therefore, it was necessary in this industrially oriented project to explore the LAH-process for these types of joint preparation. As a reference flat milled edges and milled V-joints (2,5º+2,5º or 3,5º+3,5º) were also welded.

Laser cut edges

Laser cutting has become a most important industrial blanking process for sheet metal up to 20-25 mm thickness. The laser cut surface is normally characterised by a surface roughness that is changing from a smooth area in the upper part to a slightly rougher zone lower down. The overall surface roughness also depends on the cutting machine and laser parameters used as well as the maintenance of the machine. The amount of oxides and dross may also vary considerably. Thereby laser cut surfaces exhibit a non-uniform quality, which an industrial welding process must be able to cope with. In this project, the industrial partners in the project prepared the laser cut specimens by using their production cutting machines.

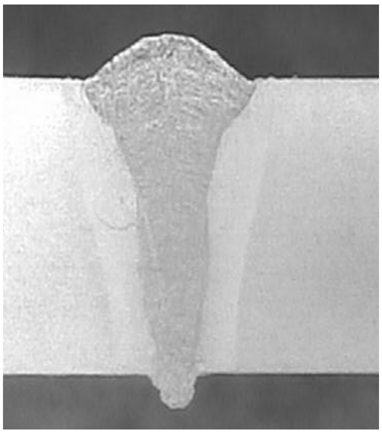


Figure 3.2.1. DOMEX 390 XP, 8 mm, v= 0,8 m/min, P_L=5,2 kW; P_{MIG}= 3,3 kW; wire feed 10 m/min, He/Ar, (spec. HL16)

The maximum laser welding speed (the speed at which full penetration was achieved) for 8 mm thick mild steel with milled edges was determined to be 0,8 m/min at 5,2 kW on the work piece by experiments. In general, LAH- welding of laser cut surfaces with no additional gap introduced, required a lower welding speed, to achieve full penetration. But if a gap of 0,4 mm was introduced, a welding speed of 0,9 m/min or more was reached.

Figure 3.2.1 shows a typical appearance of LAH-welded laser cut edges.

When the sheet thickness is increased to 10 or 12 mm the weld appearance changes significantly. The root side becomes very rough and irregular showing large drops of the weld metal. This phenomenon is due to the oxides on the cut edges and is discussed in section 3.3. By introducing a controlled gap of 0,5 mm acceptable weld geometries could be obtained even for 12 mm material but the weld material contains some large pores. The best results were achieved when the oxides on the cut edges were removed.

Sheared edges

Shearing is also a frequently used blanking process in industry as it is cheap and fast. The sheared edges though, normally show a plastic deformation and might be considered as bevelled. These edges are not suitable for autogenous laser butt welding, as there will be a lack of material and as a consequence a weld undercut will be produced.

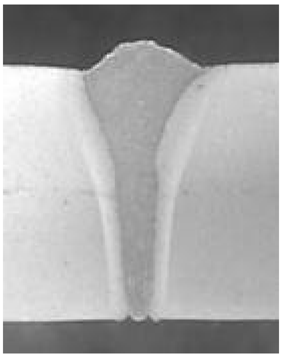


Figure 3.2.2. DOMEX 390XP, 8, mm. Sheared edges. P_L= 5,2 kW; P_{MAG}= 3,8 kW; v=1,3 m/min; wire feed=8 m/min; He/Ar/CO_2 (spec.HK10)

Sheared edges are however weldable with the LAH-process giving high quality welds. In our experiments, the sheets were oriented with the burnish upwords, thereby introducing a gap on the topside of the sheets. Figure 3.2.2 shows the typical weld appearance. It must be noticed, that the maximum welding speed is increased approx. 45% using this blanking process.

<u>Plasma cut edges.</u>

Plasma cutting is a third blanking process frequently used in industry. The plasma cut edges shows a bevel (chamfer) of approximately 10-15º, giving a V-joint of 20-30 º to be welded. The LAH-welding appearance is good at sheet thickness of 6 mm, figure 3.2.3, but it is only possible to achieve acceptable welds for 12 mm material when the oxides from the cutting process are removed, figure 3.2.4.

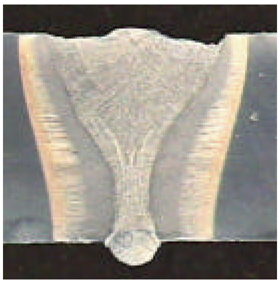


Figure 3.2.3. WELDOX 960, 6 mm. plasma cut edges. P_L= 5,2 kW; P_{MAG}= 6,7 kW, v= 1,5 m/min; wire feed=22m/min;: He/CO_2 . (spec HD 18)

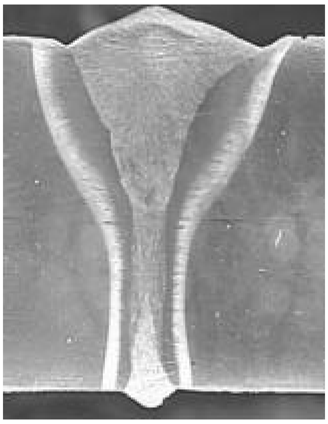
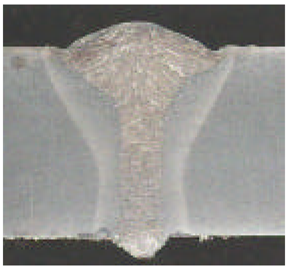
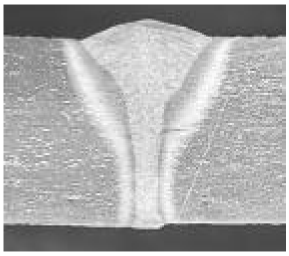


Figure 3.2.4, WELDOX 960, 12 mm, plasma cut edge, oxide removed, v=1,4 m/min, wire feed=14,5 m/min, He/Ar/CO_2 (spec FD10)

As a reference, the weld geometry for milled edges is shown in figure 3.2.5.



a.



b.

Figure 3.2.5. Weld geometry of milled edges DOMEX 390, 8 mm.

. *a) P_L=5,2 kW; P_{MIG}=3,1 kW, w=0,9 m/min, wire feed 14/m/min He/Ar bevel 3,5° + 3,5° (spec. HC19)*

b). P_L= 11,4 kW; P_{MIG}= 4,9 kW w= 1,8 m/min, wire feed 9 m/min He/Ar, bevel 2,5° +2,5° ,(spec FA7)

3.3 Influence of oxides

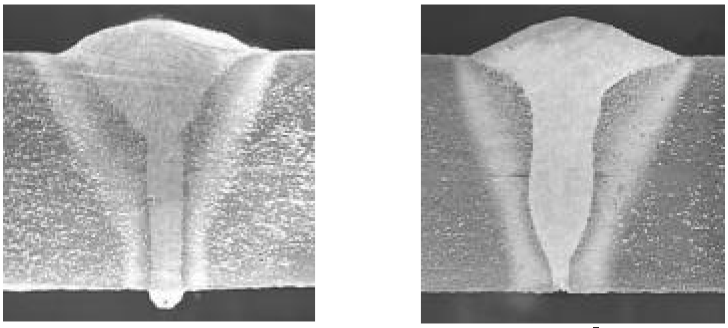
When laser butt welding of laser or plasma cut sheets, the oxides from the cutting process, if not removed, will take part in the welding process. Also oxides on the top and bottom surfaces of the sheet steel may be found and these may also influence the welding process. As industrial demands strive towards a minimum of operations in the manufacturing process, it is preferred if the LAH-welding could be performed without removing these oxides. Thus, LAH-welding tests have been performed both with and without oxides on the joint edges and on top and bottom surfaces.

Oxides on joint edges

With the 6 kW-laser, on DOMEX steels, full penetration was not achieved on laser cut 8 mm plate at a reference welding speed 0,8 m/min. Welding on 6 mm plasma cut WELDOX-steel showed full penetration without melt-through, figure 3.2.3.

With the 12 kW-laser 8 mm laser cut DOMEX-steel was welded with good result, see figure 3.1.5. 10 mm plate was welded with acceptable weld quality but increasing plate thickness to 12 mm showed excessive and irregular weld penetration, A joint gap of 0,5 mm gave a smooth weld but numerous of pores. Excessive penetration occurred also when welding WELDOX. Acceptable welds could only be achieved when oxides were removed.

The experiments show that the influence of the oxides on the joint edges on the weld quality is minor at 6-10 mm plate thickness. The maximum welding speed is reduced, as can be seen in figure 3.3.1, and the weld width is increased. But by introducing a small gap of 0,4 mm the welding speed could be increased to normal values. When LAH-welding of 12 mm material, the oxides promotes the formation of excessive and irregular weld penetration and large drops are formed on the bottom of the weld. Also the amount of pores is increased. By removing the oxides before welding high quality welds can be achieved, Figure 3.3.2.

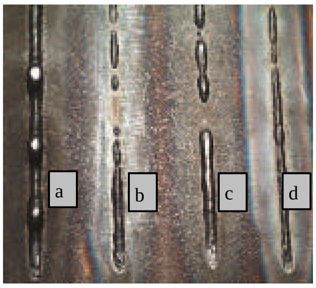


a **b**

Figure 3.3.1. Weld appearance of LAH-welding of DOMEX 390XP, 8 mm. a) oxides removed,(spec. HN11) b) oxides present at welding (spec. HN12)

Figure 3.3.2, DOMEX 390XP, 12mm, pickled sheet, laser cut, oxides removed, He/Ar, v=1,2 m/min, wire feed=8,8m/min (spec FC21)

<u>Oxides on sheet metal surfaces</u>



a. Not grinded
b. Grinded root side
c. Grinded top side
d. Both side grinded

Figure 3.3.3. Root side of BOP weld showing the influence of oxides on top and bottom surfaces at insufficient sand blasted sheet.

Also the oxides on top and bottom surfaces influence the weld quality. Especially the welding process is sensitive to the oxides on the bottom side, which causes excessive and irregular weld penetration, figure 3.3.3.

3.4 The influence of process gases

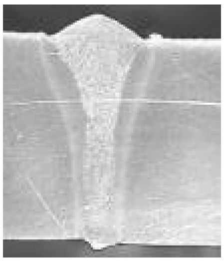
Both the mix and the flow rate of the process gas have an influence on the welding result, especially the weld reinforcement and the undercut. The gas-mixtures examined can be seen in table 3.4.1

Table 3.4.1. Used gas or gas mixtures

Gas or gas type mixtures	Number of compositions tested
He	
He/Ar (HELON®xx)	5
He/CO_2	3
He/Ar/CO_2	6
He/Ar/O_2	1
He/CO_2/O_2	1
Ar/CO_2	2

In order to suppress the formation of undercut and excessive height of the weld reinforcement, which occurs using only Helium, different gas mixtures were tested. It was found that the Helium content should be in the range of 50-80%.

To further decrease the He-content or exclude it (i.g. Ar/CO_2-mixture), in exchange to cheaper gases such as Argon or CO_2, tends to increase the plasma cloud formations, thus preventing full penetration. Useful gas mixtures were found in all Helium gas-mix combinations by which fully approved welding geometries were obtained. Especially the addition of CO_2 or O_2 was shown to be effective in order to reduce the undercuts.



Figue 3.4.1. DOMEX 390XP 8mm, milled V-joint 2,5°+2,5°. He/CO_2, v=1,3 m/min, wire ø 0,8 mm, wire feed=14 m/min,(spec. HG7)

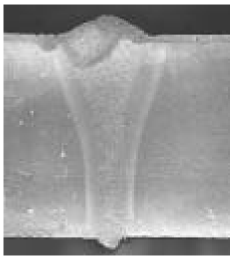


Figure 3.4.2. DOMEX 390XP 8mm, milled V-joint 2,5°+2,5°. He/Ar/CO_2, , v=1,3 m/min, wire ø 0,8 mm, wire feed=14 m/min,(spec HG10)

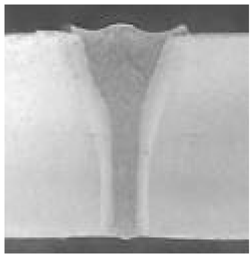


Figure 3.4.3. DOMEX 390XP, 8 mm sheared edges, He/CO_2/O_2, v=1,2 m/min, wire ø 0,8 mm, wire feed=14m/min, (spec. HM3)

4. Discussion

The results to date from investigating the LAH-process for different industrial joint preparations, shows tremendous possibilities of obtaining excellent welding results. The most promising joint preparation is shearing where an increase in welding speed of approximately 60% has been demonstrated. Here, it is possible to fully utilize the synergetic effect of the combination of laser and MIG/MAG-welding. Sheared edges if oriented properly, give a gap on the topside of the plate where the welding processes interact. The wire speed can be set rather high without giving excess weld reinforcement and thereby it is possible to achieve a spray arc, giving a smooth weld appearance. The drawbacks are the varying deformation of the sheet edges, depending of the shearing process parameters and shearing tools condition, and the necessity to orient the sheet to obtain a gap. This will make it necessary to develop a rather wide process window in order to handle the varying conditions. With this method of preparing the joint, there will be no influence of oxides from the sheet edges, which we have shown can be a problem.

The investigation so far implies that remaining oxides from the laser or plasma cutting process, will decrease the weldability and the weld quality. The worst case is for thick materials (12 mm) when welding laser and plasma cut surfaces. By introducing a small gap it is possible to get acceptable weld geometry but then porosity can be problem. Plasma cut surfaces are not possible to weld with acceptable quality for 12 mm thick material. In general, the oxides tend to reduce the viscosity and the surface tension of the melt, giving a liquid that easily produces excessive and irregular penetration. The volume of oxides increases as the plate thickness increases due to a larger area of the sheet edge, but also most likely due to slower cutting process (thicker oxide layer). An interesting observation is the widening of the weld bead when welding surfaces with oxides, figure 3.3.1 , which at the same time reduces the penetration depth. This is probably due to a complex combination of an increased Fresnell absoptivity in the weld front, the higher melting temperature of the iron oxides and the decreased viscosity of the melt. Further investigations on the subject will be necessary to fully understand the process.

Acceptable welding results have been achieved for many different combinations and mixtures of the shielding gas in the LAH-welding process, indicating a rather low sensitivity to this particular weld parameter. Shielding gas containing CO_2 or O_2 in the He/Ar mixture, will improve the formation of smooth weld reinforcements thereby suppressing the formation of undercuts. The relatively low sensitivity to the type of shielding gas indicates that the

LHA-process is rather stable. (The stabilizing effect of the MIG/MAG-arc by the laser beam and the laser plasma formation has been discussed before by other researches.) Helium will be the predominant gas in the gas mixture in order to suppress excessive plasma formation, which would decrease the penetration depth. The amount of Argon and CO_2 or O_2 in the gas mixture may then be varied rather freely, whilst still obtaining acceptable welding results.

From an industrial point of view, the possibility to weld different kinds of joint preparation where gaps may be present and still obtain very high welding speeds and excellent weld quality is a very interesting feature of the LAH-welding technique. This will give the process a great potential for the future use in many different applications.

5. Conclusions

Laser-arc-hybrid welding has been shown to be an effective welding process for joining of thick steel plates. The process has been shown to be capable of handling different kinds of joint preparation methods such as; laser, or plasma cutting and shearing, thereby expanding the industrial production capabilities of the high power laser. For sheared edges the welding speed can be increased 60%. Laser cut material with the oxides from the cutting process still present will give acceptable welds up to approximately 10 mm thickness, but for 12 mm material the oxides have to be removed in order to obtain welds without pores and excessive and irregular weld penetration. The LAH-process is rather insensitive to the shielding gas used, but the best results have been obtained for a mixture of He (predominant), Ar and CO_2 or O_{2}.. In the future, it is expected that the LAH-welding process will be used in many applications, where thick materials are joined to form high quality components or products at high productivity.

6. Acknowledgement

This work has been performed within the framework of RACER, a national Swedish R&D- programme financed jointly by the The Swedish Agency for Innovation Systems, VINNOVA, and the participating industrial partners. The financial support is greatly acknowledged. The authors would also like to thank the steering committee for the RACER programme for valuable input and discussions.

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