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PECULIARITIES OF HYBRID LASER-ARC WELDING OF STAINLESS STEEL*

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The use of hybrid laser-arc welding laser + MAG for joining elements of large structures of stainless steel is a relatively new problem. The paper discusses the issues of technology of hybrid welding of austenitic steel X2CrNi18-9 and austenitic-ferritic steel X2CrNiMoN21-5-1 using a disc laser of 12 kW capacity. The technological conditions of hybrid welding with a full penetration of butt joints of steel with a thickness of 8, 12 and 20 mm, as well as T-joints with a butt weld with a partial penetration were determined. The typical defects in welds of high-alloy stainless steels, produced by hybrid welding, were indicated. 5 Ref., 20 Figures.

Keywords: *hybrid welding, laser+arc, active gas, stainless steels, arc and beam parameters, location of sources, typical welding defects*

Hybrid laser-arc welding is a process which has been intensively studied, developed and implemented during recent years [1–5]. The application of hybrid laser-arc welding using consumable electrode (HLAWCE) laser + welding with solid wire in inert and active gases (ISO 4063: 521 + 135 process) for joining parts of large structures of stainless steel is a relatively new problem. The method of hybrid welding is technologically complex – it is necessary to select the parameters of welding arc and laser beam, a suitable mixture of shielding gas and a spatial arrangement of both used energy sources (end of electrode wire and spot of beam focusing) with respect to each other and to the line of edge butt for each type of joint.

This paper discusses the technology of hybrid laser + MAG welding of austenitic steel X2CrNi18-9 and ferritic-austenitic steel X2CrNiMoN21-5-1 with the use of a disc laser of 12 kW power and a special hybrid head.

Results of experiments. Technological tests for selection of shielding gas for hybrid welding of steel X2CrNi18-9 with electrode wire G 19 9 L Si and welding of steel X2CrNiMoN21-5-1 with electrode wire G 22 9 3 N L showed that the stability of hybrid process, the required shape of welds and minimal spattering are provided by a gas mixture of 97.5 % Ar + 2.5 % CO_2.

The penetration depth and width of the butt joint were measured for the four values of diameter of the used light guide (200, 300, 400 and 600 μm) and two directions of moving the hybrid head: with a laser as the leading heating source (designation *L* — *A*) and an electric arc as a leading heating source (designation *A* — *L*). The measurements confirmed that regardless

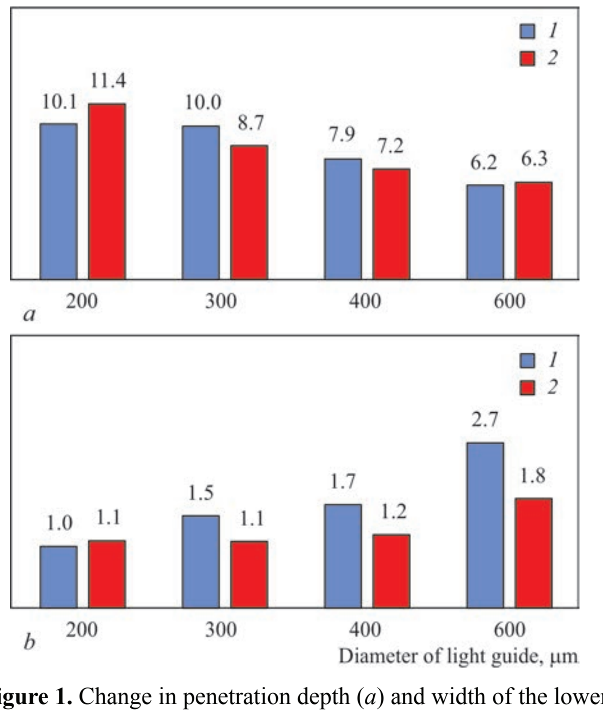

Figure 1. Change in penetration depth (*a*) and width of the lower part (*b*) of the weld for different values of diameter of the used light guide and the direction of moving the hybrid head. For *a*: *1* — penetration depth *L* — *A*, mm; *2* — penetration depth *A* — *L*, mm; for *b*: *1* — width of the lower part of the weld *L* — *A*, mm; *2* — width of the lower part of the weld *A* — *L*, mm

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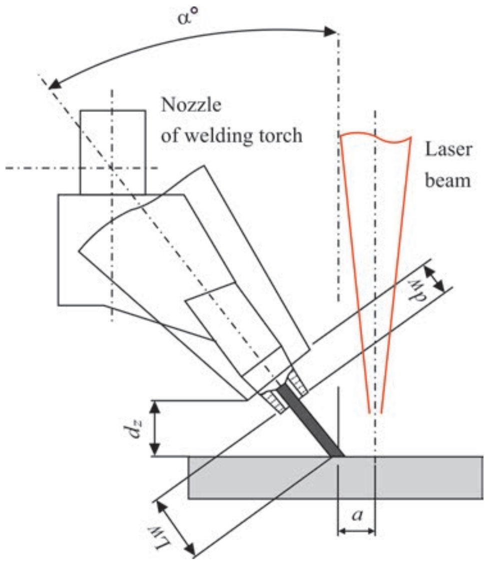

Figure 2. Spatial position of the system «laser beam – welding head MAG – element to be welded», laser beam perpendicular to the material: *a* is the distance from the end of the wire to the zone of laser beam focusing, α is the inclination angle of welding torch MAG relative to the laser beam axis; L_w is the electrode stickout; d_z is the distance from gas nozzle to element, d_w is moving forward of contact end from gas nozzle

of direction of welding, penetration depth is comparable for individual diameters of applied light guides, and with an increase in diameter of the light guide, penetration depth decreases and the width in the lower part of the weld increases (Figure 1).

From the point of view of maximizing penetration depth, the most suitable solution seems to be the use of a light guide with the smallest diameter. However, due to the stability of HLAWCE welding process (stability of the gas-dynamic channel formed as a result of a laser beam effect) and to provide the width of the weld in the region of its lower part at a level of more than 1 mm, it is recommended to choose a light guide with a larger diameter. Further, a light guide with a

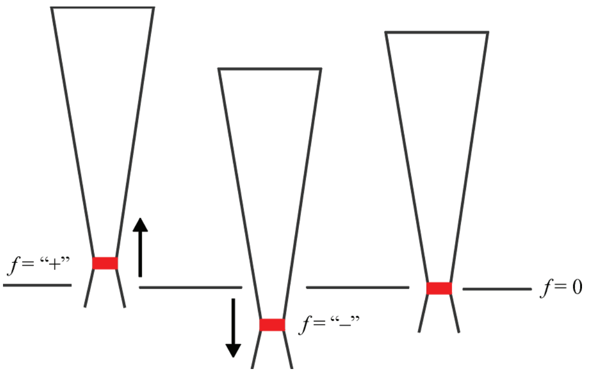

Figure 4. Location of laser beam focus relative to the surface of the specimen (*f* = 0 — position of the focus on the sheet surface)

diameter of 400 μm and with the direction of welding *A* — *L* was used.

An important group of parameters is a mutual spatial position of the system «laser beam – MAG welding torch – element to be welded» (Figure 2).

The most advantageous for automatic MIG/MAG welding is setting of a holder perpendicular to the material being welded (angle α = 0°). In the process of hybrid welding, laser beam is responsible for the obtained penetration depth to a much greater extent than welding arc and therefore it is set perpendicular to the material being welded.

For the technological head used in the study, the inclination angle of the torch holder MAG was selected as α = 25° and the distance from the end of the wire to the focusing zone of laser beam was selected as *a* ≤ 2 mm, providing a safe (without collisions with laser beam) welding process. Increasing the distance α to about 4 mm does not have a significant effect on the process. The produced weld shape is comparable (Figure 3, *a*, *b*). A further increase in the distance causes a decrease in the volume of the weld (Figure 3, *c*) and, in extreme case, a noticeable decrease in the penetration depth (Figure 3, *d*).

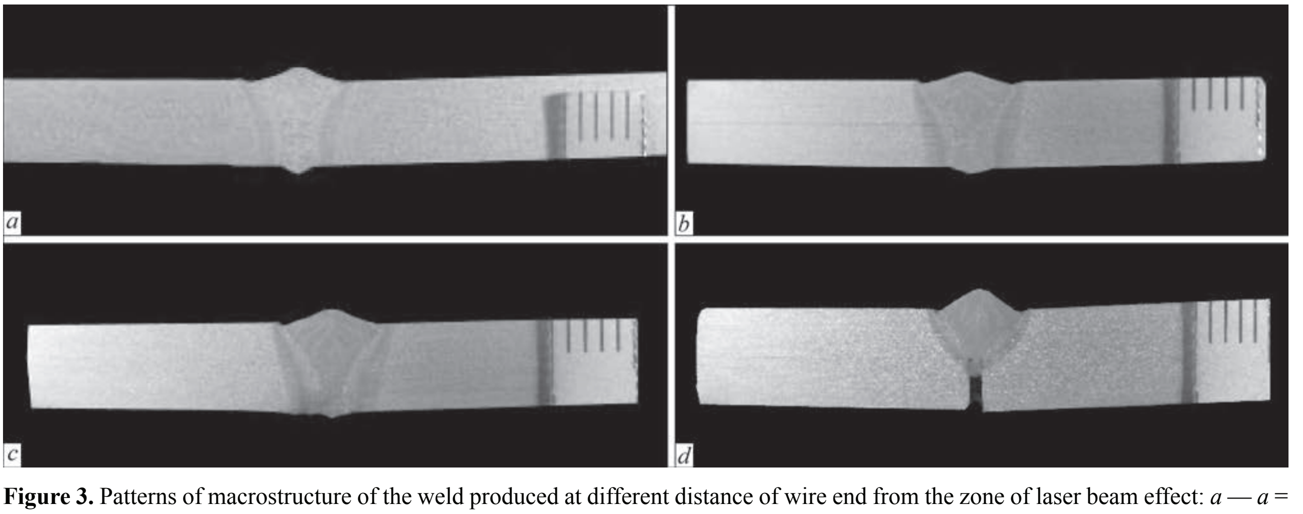

Figure 3. Patterns of macrostructure of the weld produced at different distance of wire end from the zone of laser beam effect: *a* — *a* = = 2; *b* — 4; *c* — 6; *d* — 8 mm

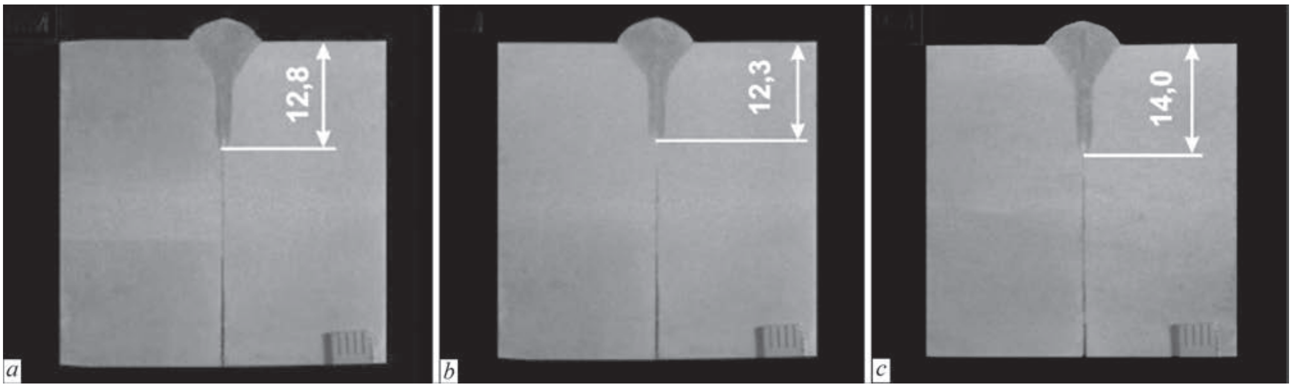

Figure 5. Macrostructure of butt joints of specimens of 40 mm thickness produced at different arrangement of laser beam focus relative to the surface of material to be welded (power of laser radiation P_l = 11 kW, welding speed v_w = 0.7 m/min, wire feed rate v_{wf} = = 11 m/min): *a* — f = 0; *b* — –5; *c* — –10 mm

A separate issue is arrangement of the laser beam focus relative to the material being welded (Figure 4). Technological tests of HLAWCE were carried out on specimens of 40 mm thickness with different setting of the position of the laser beam focal point: *f* = 0; –5 and –10 mm (Figure 4).

The penetration depth did not change significantly, it ranged from 12.3 to 14 mm (Figure 5). Based on the latter, in future it is recommended to set the position of focusing laser beam on the surface of the material being welded.

Then, the dependence of the penetration depth and geometric dimensions of welds on the power of laser beam in the HLAWCE process was studied. Depending on the power of laser beam in the range of 6–12 kW, the penetration depth was 12.5–18.5 mm. A significant effect on the penetration depth is also exerted by the gap of elements being joined, which was confirmed by tests at a gap of 0 and 0.8 mm (Figure 6).

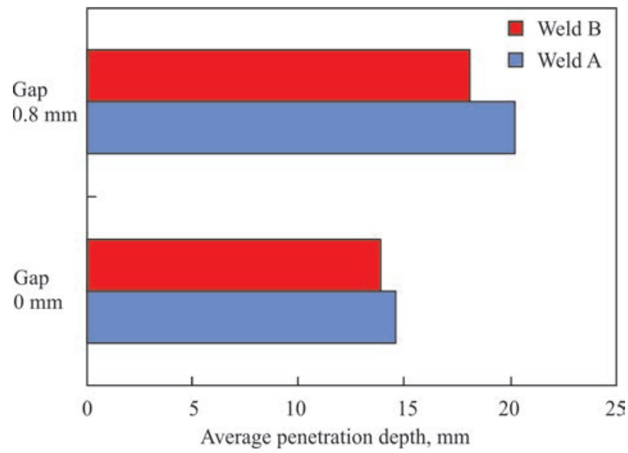

Figure 6. Average values of penetration depth of butt joints of specimens of 40 mm thickness, produced at different gap value *g* (double-sided welding, first weld — A, second — B)

Technological tests of welding butt joints with a thickness of 8, 12 and 20 mm after laser cutting (roughness of surface was respectively ≤ 11.3; ≤ 14.2 and ≤ 70.0 μm) showed that the roughness of surface of welded edges up to R_z = 70.0 μm does not cause violation of stability of the HLAWCE process. In the case of plasma-arc cutting in the installation YUN-3000M, applying the mixture $Ar–H_2$ as a plasma-forming gas, the roughness is lower than 70.0 μm and the surface is also suitable for HLAWCE welding.

The bevel of edges, characteristic for plasma cutting can cause axial displacement of individual welds in a double joint. The bevel of edges in the specimens with a thickness of 25 mm and a length of 600 mm was measured after industrial plasma cutting at an industrial partner. The measurement results showed that the bevel of edges is relatively large and at an unfavourable combination of sheets for welding, when the

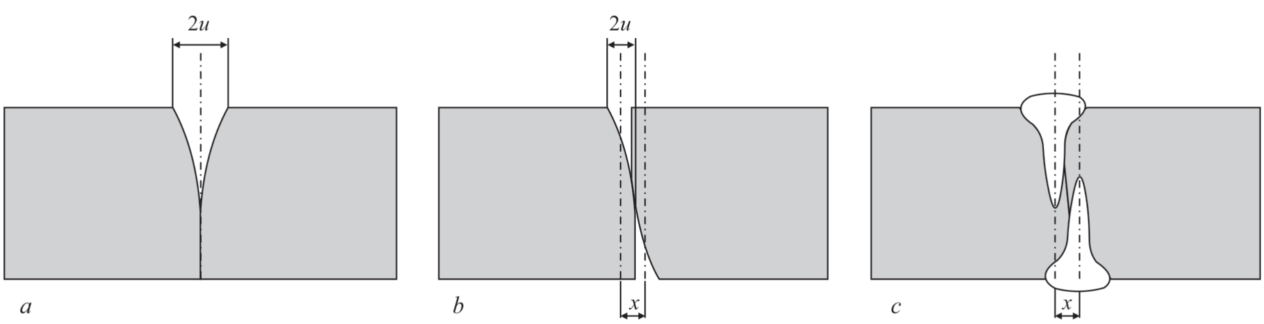

Figure 7. Different methods of combining parts, prepared for welding, after plasma cutting: *a* — summing of bevel at one side of a butt; *b* — displacement of *x* axis of separate welds in a double joint; *c* — visualization of absence of penetration, arising as a result of combination of parts with the bevel

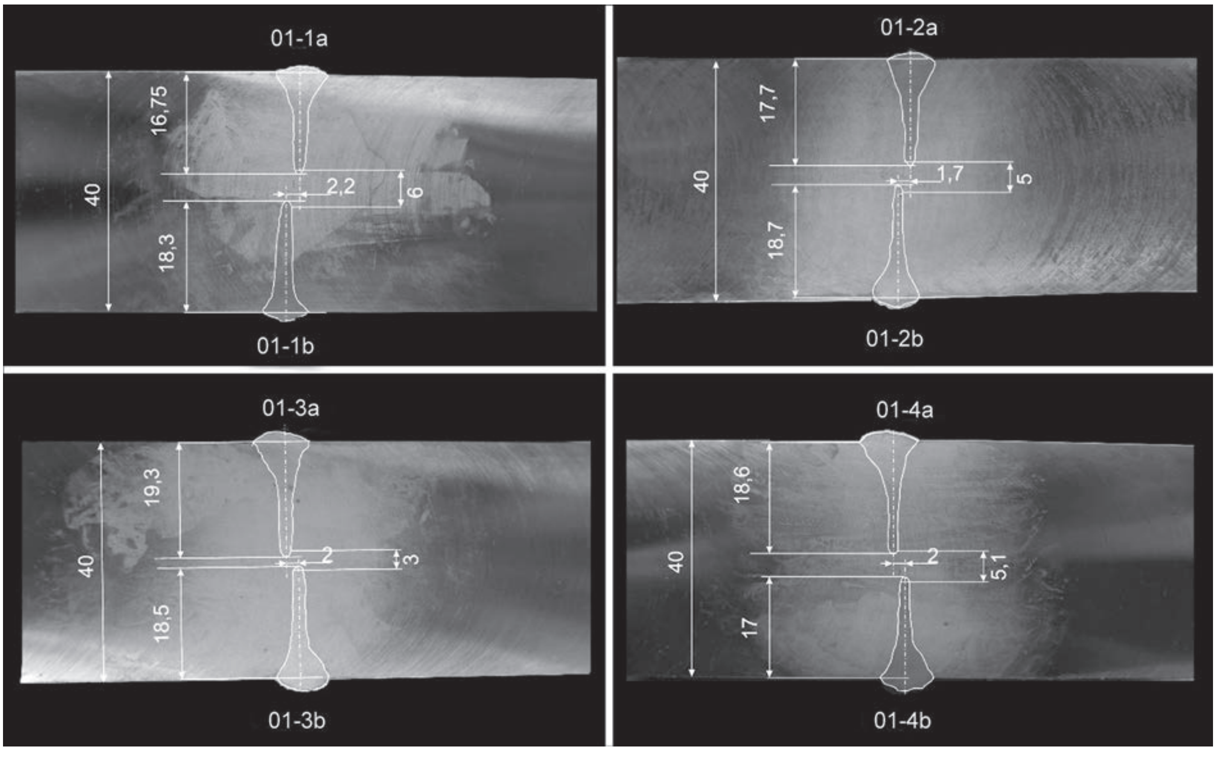

Figure 8. Arrangement and dimensions of welds of double-sided hybrid joint of sheets of 40 mm thickness with edge preparation after industrial plasma cutting and grinding

bevel is folded, on the surface of the sheets a gap of more than 2 mm width is formed. As the thickness of a sheet increases, the bevel becomes larger.

The appeared bevel leads to the fact that combination of parts in the butt joint can be obtained in two ways (Figure 7). In the first case, the bevel is summed on a one side of a butt of the parts, causing an increase in the gap. In the second case, the bevels are located on the opposite sides, and that allows mating parts at a smaller gap. However, a risk of axial displacement of individual welds in a double-sided weld exists. In this case, insufficient penetration in the central part of the joint is probable, despite providing the appropriate penetration depth of individual welds (Figure 7, *c*).

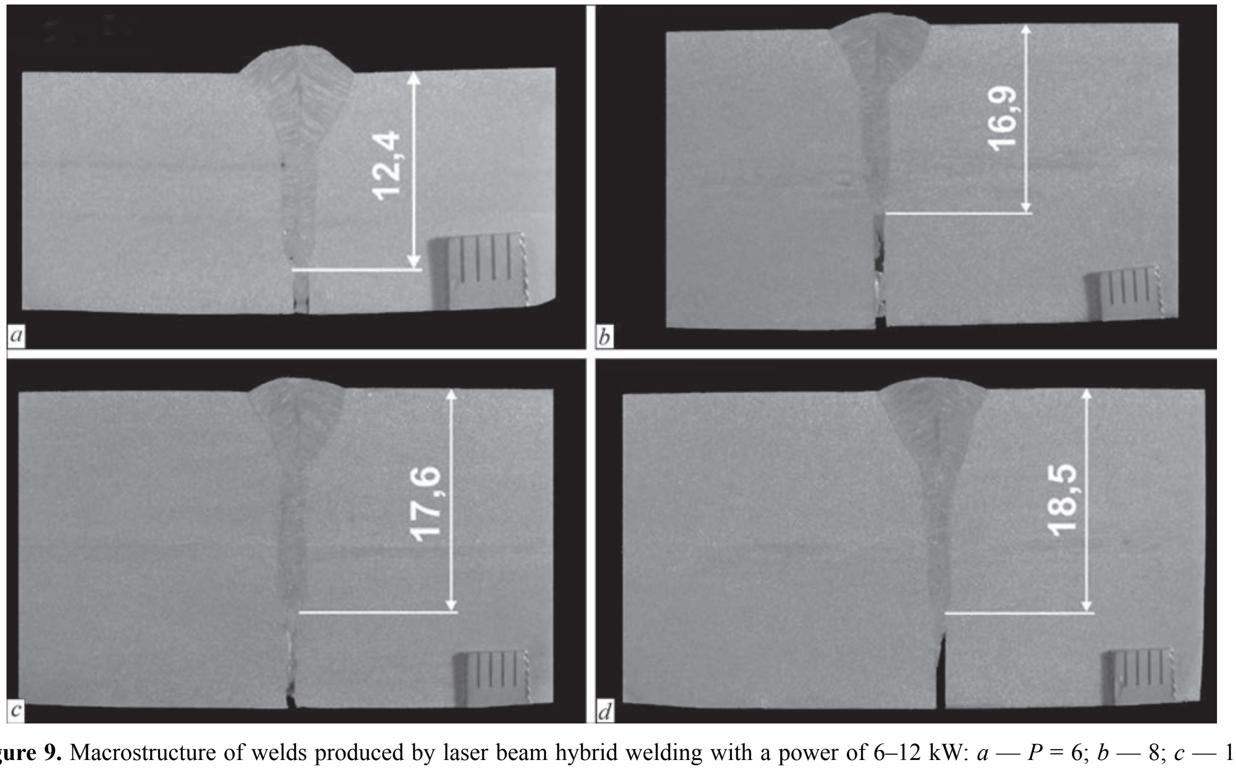

Figure 9. Macrostructure of welds produced by laser beam hybrid welding with a power of 6–12 kW: *a* — *P* = 6; *b* — 8; *c* — 10; *d* — 12 kW

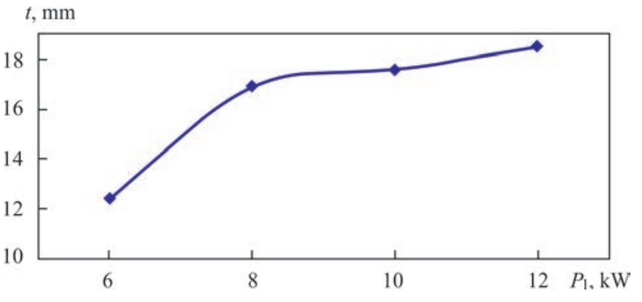

Figure 10. Dependence of penetration depth t on the power of laser beam P_l in HLAWCE

The considerations mentioned above confirm the results of HLAWCE of sheets of 40 mm thickness after industrial plasma cutting on the specimens provided by an industrial partner. Due to the fact that during mating of sheets in accordance with Figure 7, *a*, the gap $2u$ was more than 3 mm, an attempt was made to mate sheets for welding in accordance with the second method (Figure 7, *b*) in order to obtain the smallest possible gap. After welding, metallographic specimens in four selected locations along the length of the welded joint were manufactured. Macrosections of the produced joints are shown in Figure 8.

The average penetration depth was about 18 mm, which did not allow producing a double-sided welded joint of 40 mm thickness with a full penetration. On metallographic sections, displacement of axes of individual beads was observed as a result of using plasma cutting as a method of butt joint preparation. Due to the need in maintaining coaxial alignment of individual weld beads in a double-sided weld, it is necessary to provide a method of edge preparation which will guarantee a side edge, perpendicular to the sheet surface. For materials of up to 15 mm thick, laser cutting is sufficient. For thicker materials edge machining may be required.

To determine the effect of laser beam power in the HLAWCE process on the penetration depth and the shape of welds, welding of sheets of 40 mm thick was carried out with the edge surface after milling, with a gap of 0.8–1.0 mm, varying the power of laser radiation from 6 to 12 kW (Figures 9–11).

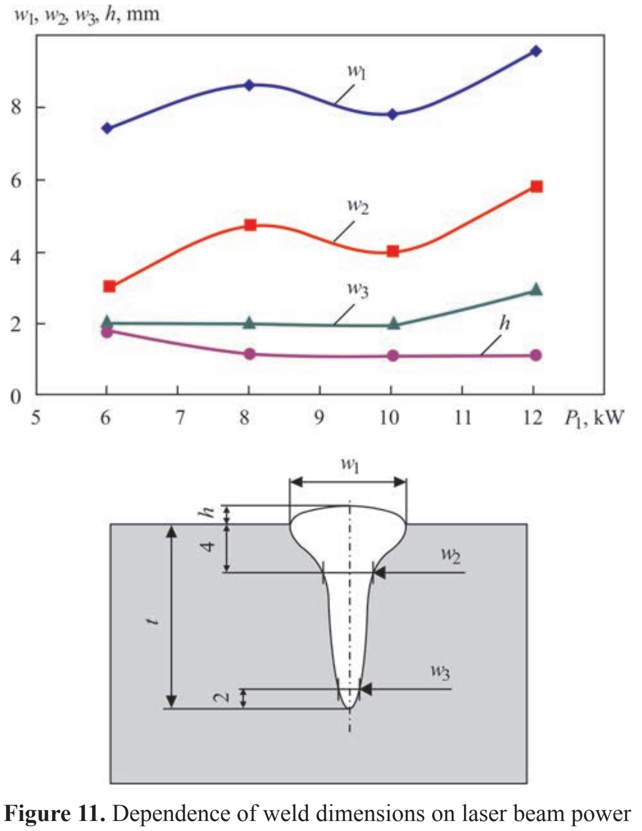

Figure 11. Dependence of weld dimensions on laser beam power in HLAWCE

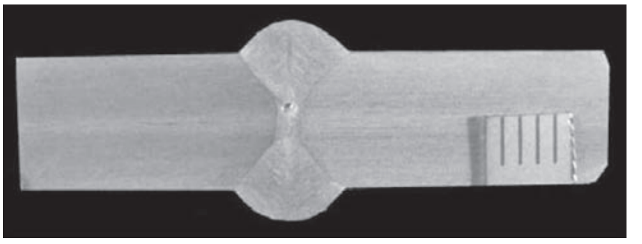

Figure 12. Macrostructure of double-sided welded joint of 8 mm thickness (P_l = 5.0 kW, v_w = 1.2 m/min, v_{wf} = 8.4 m/min, arc current I_a = 225 A, arc voltage U_a = 21 V, welding input energy Q = 3.9 kJ/cm)

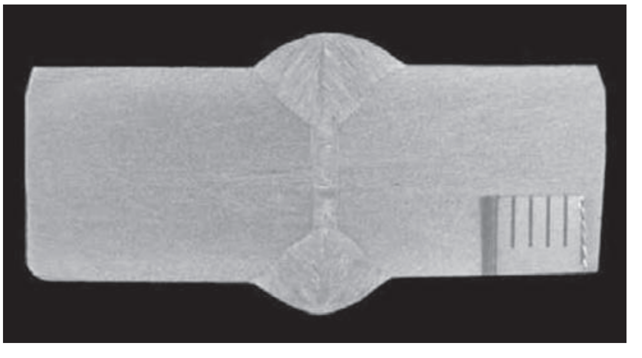

Figure 13. Macrostructure of welded joint of 12 mm thickness (P_l = 5.5 kW, v_w = 1.2 m/min, v_{wf} = 8.6 m/min, arc current I_a = = 250 A, arc voltage U_a = 28 V, Q = 6.3 kJ/cm)

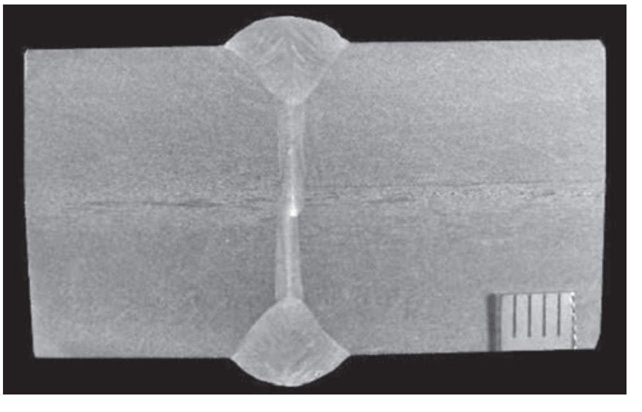

Figure 14. Macrostructure of welded joint of 20 mm thickness (P_l = 6.5 kW, v_w = 1.0 m/min, v_{wf} = 8.5 m/min, arc current I_a = = 235 A, arc voltage U_a = 27 V, Q = 7.7 kJ/cm)

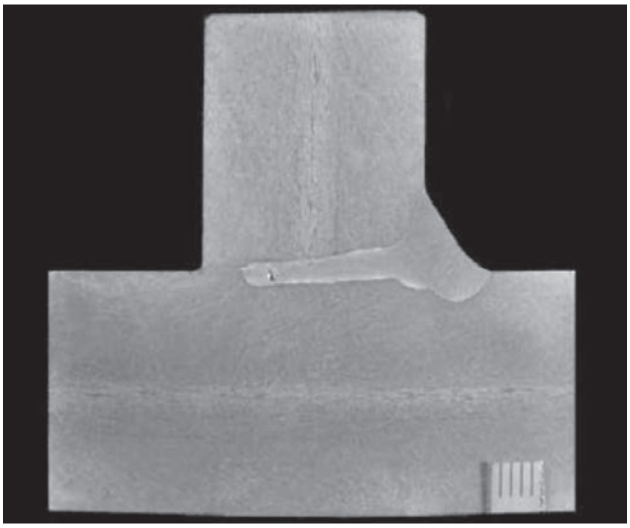

Figure 15. Macrostructure of one-sided T-joint of 20 mm thickness with partial penetration (P_l = 10.0 kW, v_w = 0.7 m/min, v_{wf} = = 8.5 m/min, I_a = 227 A, U_a = 29 V, Q = 14.2 kJ/cm)

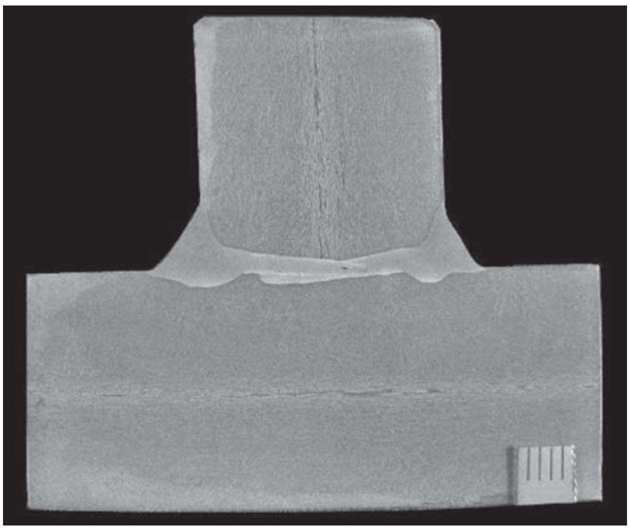

Figure 16. Macrostructure of double-sided T-joint of 20 mm thickness (P_l = 10.0 kW, v_w = 1.3 m/min, v_{wf} = 8.5 m/min, I_a = = 241 A, U_a = 28 V, Q = 7.7 kJ/cm)

Figure 17. Back side of T-joint of sheets of 20 mm thickness — humps

Figure 18. Longitudinal section of butt joint of 8 mm thickness – humps and porosity

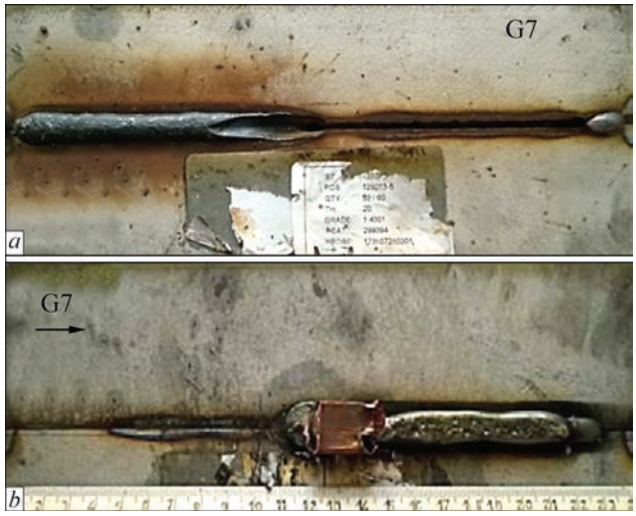

Figure 19. Appearance of one-sided welded joint with a thickness of 20 mm (P_l = 11.0 kW, v_w = 0.4 m/min, v_{wf} = 8.5 m/min, I_a = = 222 A, U_a = 31 V, Q = 21.5 kJ/cm): *a* — face side — unfilled groove and burn-through after about 110 mm; *b* — root side — lack of penetration, excess melting and penetration of copper pipe for forming gas supply

With an increase in the power of laser beam, penetration depth increases, however, not according to linear dependence. A change in the power of laser beam from 6 to 8 kW leads to an increase in the penetration depth by about 4.5 mm (Figure 10). With a further increase in the power by 2 kW, the penetration is higher by 0.7 mm. At a power of laser beam being 12 kW, the penetration depth was 18.5 mm. With an increase in the laser beam power by 50 %, from 8 to 12 kW, the penetration depth is increased by 1.6 mm, i.e., only by 9 %.

Based on these results, the modes of laser + MAG hybrid welding of double-sided butt joints of steels X2CrNi18-9 and X2CrNiMoN21-5-1 with a thickness of 8, 12 and 20 mm (Figures 12–14) in flat position, butt joints of these sheets with backing welding using MAG and HLAWCE method, as well as one-sided and double-sided T-joints were determined (Figures 15, 16).

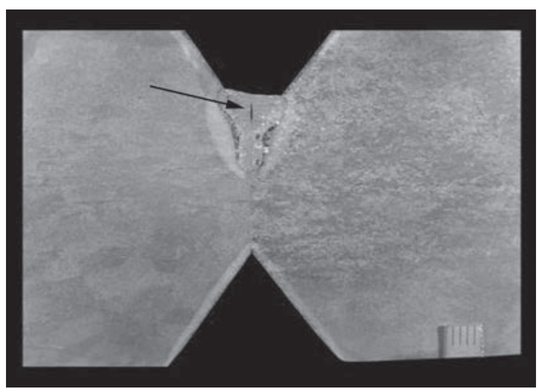

Figure 20. Macrostructure of root weld of butt joint of steel X6Cr13 with a crack (indicated by an arrow)

Non-destructive and destructive tests of a double-sided butt joint of plates of steel X2CrNi18-9 with a thickness of 12 + 12 mm (see Figure 13) showed that they meet the requirements of the standard ISO 15614-14 for certification of hybrid welding procedure.

Defects in welds of HLAWCE. Specific defects of one-sided welds made by hybrid welding include unstable formation of back side (root) of welds and porosity (Figures 17, 18).

In one-sided welding of hybrid butt joints, typical defects are lack of penetration at the weld root and excess of penetration. At the beginning there is a region of the weld without a full penetration, then, a short region with a full penetration goes, followed by a burnout and leakage of liquid metal of weld pool (Figure 19).

Defects of welds of high-alloy steels, made by hybrid welding, include also hot cracks. The susceptibility to hot cracks formation was observed in case of producing a root weld of a butt joint of steel X6Cr13 of 50 mm thickness with root face of 15 mm (Figure 20).

Conclusions

1. Hybrid laser + MAG welding allows producing double-sided butt joints of steel X2CrNi18-9 and X2CrNiMoN21-5-1 with a thickness of 8, 12 (one-sided) and 20 mm (double-sided), as well as butt joints with backing welding by the MAG and HLAWCE method with a full penetration in flat position.

2. Hybrid welding allows producing T-joints of sheets susceptibility of 8, 12 and 20 mm thickness with a butt weld with a partial penetration, often replacing T-joints with a fillet weld, as well as T-joints of sheets of up to 20 mm thickness with a butt weld in flat position.

3. Specific defects of welds of high-alloy stainless steels made by hybrid welding include: unstable formation of the root of welds, porosity and hot cracks.

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