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ANALYSIS OF THE CONDITION OF EDGES OF SHIPBUILDING STEEL PLATES PRODUCED BY AIR AND WATER-AIR PLASMA CUTTING

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The purpose of welding edges produced by plasma cutting without additional processing is to reduce the cost of producing welded joints. In the thickness range of 8–20 mm for carbon steels, air plasma cutting with a transferred arc is the most promising method [1]. To further improve the quality of this process, it has been proposed to introduce a certain amount of water or water vapor into the plasma-forming jet or the shielding air. This approach not only improves the quality of the formed cut edges, but also reduces the heat-affected zone (HAZ) and saturation with atmospheric gases, primarily nitrogen [2].

Studies of the effect of the total water flow rate supplied to the nozzle during plasma cutting in plasma-forming media of air + water and oxygen + water were carried out by varying the water flow rate in the range of $(1.6–8.3) \times 10^{-3}$ L/s, or 0.1–0.5 L/min. In this case, the water flow rate into the nozzle channel was $(0.45–2.32) \times 10^{-3}$ L/s, or (0.03–0.14) L/min.

The water supplied into the nozzle channel partially evaporates and dissociates into hydrogen and oxygen, which, mixing with the main plasma-forming medium, create a combined plasma-forming environment in which plasma-chemical processes of binding atmospheric nitrogen occur, making it possible to reduce nitrogen saturation of the cut edges. In addition, the water constricts and densifies the plasma jet within the nozzle channel, providing higher energy characteristics.

We have established that, at a constant cutting current, due to the reduction in the cross-sectional area of the plasma jet, the current density increases by a factor of 1.3–1.7, and the voltage increases by 25–30 V compared with plasma cutting in an air plasma-forming medium. The penetrating capability of the plasma increases noticeably, improving PAWEDABAGAS increasing the perpendicularity of the cut edges. The effect of water additions on pore formation during subsequent submerged arc welding is shown in Table 1.

Table 1. Dependence of pore formation during welding on the water flow rate during plasma cutting

No	Cutting side	Plasma-forming medium	Water consumption, x10^{-3} l/s	Cutting speed, mm/s	F_{por}, mm^2	F_{pa}, cm^2	F_{por} / F_{pa}
1	Left	Air + water	1,6	36	218…234/225	40	5,5…5,9/5,6
	Right				210…216/213	40	5,2…5,4/5,3
2	Left		3,3		208…218/215	40	5,2…5,5/5,3
	Right				103…112/105	50	2,06…2,24/2,1
3	Left		3,6		190…220/200	50	3,8…4,4/4,0
	Right				50…75/60	50	1,0…1,5/1,2
4	Left		4,6		118…151/130	40,7	2,9…3,7/3,2
	Right				0,0	40,7	0,0
5	Left		5,6		100…133/111	37	2,7…3,6/3,0
	Right				0,0	37	0,0
6	Left		8,3		200…220/208	40	5,0…5,5/5,2
	Right				20…44/28	40	0,5…1,1/0,7
7	Left	Oxygen + water	1,6	42	60…80/68	40	1,5…2,0/1,7
	Right				24…44/32	40	0,6…1,1/0,8
8	Left		3,3		80…100/90	50	1,6…2,0/1,8
	Right				0,0	50	0,0
9	Left		5,6		125…250/140	50	2,5…3,0/2,8
	Right				180…210/190,5	50	3,6…4,2/4,2
10	Left		8,3		180…205/185	50	3,6…4,1/3,7
	Right				230…280/250	50	4,6…5,6/5,0

Note: $F_{пор}$ – total pore area in the weld cross-section; $F_{пр}$ – average pore area.

In all cases, the largest number of pores was obtained during submerged arc welding of carbon steel plates assembled with left-hand edges. It was established that increased nitrogen saturation of the left or right plasma-cut edge is associated with the direction of swirling of the plasma flow.

When the plasma flow rotates clockwise, the largest number of pores is obtained in the left-hand edge. The minimum number of pores is achieved at a water flow rate to the nozzle of (4.6–6.6) × 10^{-3} L/s. The plasma-forming medium is air + water. No pores are observed in the right-hand edges. In the left-hand edges, the porosity decreases from 5.6 to 3.0.

For the oxygen + water plasma-forming medium, the range of variation of the water flow rate is significantly narrower and amounts to (3.0–3.6) × 10^{-3} L/s. Increasing the water flow rate above 3.6 × 10^{-3} L/s leads to a sharp increase in weld porosity. Unlike the pores with a matte surface that occur in welds after air plasma cutting, the pores formed after cutting in an air + water medium at a water flow rate above 6.6 × 10^{-3} L/s have a silvery appearance and are caused by excessive hydrogen content.

Changes in the flow rate of the plasma-forming gas also affect weld porosity. During welding of the right-hand edges, porosity increases sharply when the plasma-forming gas flow rate exceeds 1.8 L/s. The results of the study are presented in Table 2. The influence of cutting speed on pore formation was evaluated over a range of 16.7 to

50 mm/s. As the cutting speed increases, weld porosity decreases more noticeably for welding along the left-hand edges. The results of the study are presented in Table 3.

Table 2. Dependence of pore formation during submerged arc welding on the consumption of plasma-forming medium during cutting

No	Cutting side	Plasma-forming medium	Plasma-forming medium flow rate, l/s	Water consumption, x10^{-3} l/s	F_{por} mm^2	F_{pa} cm^2	F_{por} / F_{pa}
1	Left	Air + water	0,83	5,0…5,6	0,0	37	0,0
	Right				0,0	37	0,0
2	Left		1,33		72···96 80	40	1,8···2,4 2,0
	Right				0,0	40	0,0
3	Left		2,16		36···58 49,5	45	0,8···1,3 1,1
	Right				122···143 134	42	2,9···3,4 3,2
4	Left	Oxygen + water	0,83	3,0…3,3	188···208 200	40	4,7···5,2 5,0
	Right				7,4···26 14,8	37	0,2···0,7 0,4
5	Left		1,33		128···148 140	40	3,2···3,7 3,5
	Right				0,0	40	0,0
6	Left		2,16		37···50 46	42	0,8···1,2 1,1
	Right				189···223 202	42	4,5···5,3 4,8

Table 3. Dependence of pore formation during submerged arc welding on cutting speed

No	Cutting side	Plasma-forming medium	Plasma-forming medium flow rate, l/s	Cutting speed, mm/s	F_{por} mm^2	F_{pa} cm^2	F_{por} / F_{pa}
1	Left	Air + water	1,33…1,5	16,7	152···174 163	37	4,1···4,7 4,4
	Right				32···52 40	40	0,8···1,3 1,0
2	Left			33,3	122···134 126	42	2,9···3,2 3,0
	Right				12···32 20	40	0,3···0,8 0,5
3	Left			50,0	4···16 8	39	0,1···0,4 0,2
	Right				0,0	42	0,0

It was found that a continuous solid layer saturated with nitrogen, up to 0.03 mm deep, forms along the cut edge. The addition of hydrocarbons to the air plasma, as well as water, promotes nitrogen conversion. In this case, a white nitrided layer on the cut edges is not observed. The metallographic study data are presented in Table 4. The addition of both water and hydrocarbons (about 10%) to the air plasma eliminates pore formation during welding. Adding water during oxygen plasma cutting prevents the formation of pores caused by air ingress into the cut cavity, similar to oxygen plasma cutting under water on NUMOREX and TELEREX machines.

Table 4. The influence of the plasma-forming environment on the saturation of cutting edges with nitrogen.

No. of grinds	Plasma-forming medium	Depth of nitrided layer, mm	HAZ, mm	Microhardness, MPa
1	Air + water (reverse polarity)	Not observed	0,46…0,5	5200, 4120, 3620, 3210,2560,2300
2	Air (reverse polarity)	Solid white layer up to 0.03	0.45	6100, 5760, 3800, 3110, 2290

Experiments confirmed the hypothesis of the existence of an optimal range of water vapor concentrations in the plasma. This range is limited at the lower end by the amount of vapor (the hydrogen source) required to prevent nitrogen-induced pores during welding, and at the upper end by pores caused by hydrogen. The optimal range of water additions to air plasma to prevent pore formation is (1.2–1.8) × 10^{-3} L/s, which corresponds to 120.4–189.2 L/min or 2.1–3.1 L/s of vapor. In this case, the vapor content in the plasma is 13–19%.

The range of water additions to air plasma to ensure the perpendicularity of cut edges according to GOST 14792-80 is (0.46–1.31) × 10^{-3} L/s, meaning that both the lower and upper limits of this range are below those required to prevent pore formation. Therefore, the lower limit was set based on pore prevention at 1.2 × 10^{-3} L/s, or 0.07 L/min, while the effect of the upper limit of 1.88 × 10^{-3} L/s on cut edge perpendicularity was additionally tested, since previous studies had only been conducted up to a flow rate of 1.31 × 10^{-3} L/s. The study showed that at a water flow rate into the air plasma of 1.88 × 10^{-3} L/s, the edge perpendicularity does not exceed 1 mm for an 8 mm thick sheet, thus meeting the requirements of ISO 9013:2017 "Thermal cutting — Classification of thermal cuts — Geometrical product specification and quality tolerances."

Conclusions:

1. It was established that, to achieve cut edge quality acceptable for subsequent welding, the water additions to air plasma during air plasma cutting should be in the range of (1.2–1.8) × 10^{-3} L/s, or (0.07–0.11) L/min. The total water flow to the nozzle in this case was (4.28–6.4) × 10^{-3} L/s, or (0.25–0.40) L/min.

2. When using oxygen–steam plasma, the water flow into the plasma to prevent pore formation should be (0.85–1.0) × 10^{-3} L/s.

3. Studies showed that, to minimize cut edge non-perpendicularity during oxygen plasma cutting, water additions to the oxygen plasma can be recommended in the range

of (0.85–1.0) × 10^{-3} L/s, or (0.05–0.06) L/min. The total water flow to the plasma torch nozzle in this case is 0.18–0.22 L/min.

References

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