TECHNICAL SCIENCE

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IMPROVING THE QUALITY OF AIR-PLASMA CUTTING ON THE REVERSE POLARITY BY APPLYING AIR-TO-WATER MIXTURE

***Abstract**.*

In order to obtain the possibility of using both air and air-water plasma-forming media for air-plasma cutting on the reverse polarity of the current, it is proposed to use an additional external nozzle with a swirler in the plasmatron, through which water is introduced into the arc column with a consumption of up to 20% of the air consumption. Replacing the air plasma-forming medium with an air-water mixture during reverse polarity plasma cutting of carbon steel in the thickness range of 2...200 mm made it possible to: reduce the non-perpendicularity of the cutting edges up to 2.5 times; reduce the roughness of the cutting edges; reduce the size of HAZ by 20...30%; reduce the microhardness of HAZ by more than 2 times; reduce the content of oxygen impurities in the edges of the cut by 2.6 times, hydrogen by 20...25%; eliminate the nitrided layer on the edges of the cut.

***Keywords**: air-plasma cutting, reverse polarity, plasma-forming medium, air-water mixture, carbon steel, cutting edges, non-perpendicularity, roughness, HAZ size, content of gas impurities.*

1. Introduction

Marine engineering structures and the hulls of modern ships are made from sheet and profile parts of various sizes and shapes. In the hulls of transport ships, sheet parts make up 85...90% of the mass of all parts, of which parts up to 1 m long make up 12% by mass and up to 75% by quantity. Approximately a third of sheet parts may have edge grooves. The number of parts for one vessel can reach several tens of thousands [1].

High-performance cutting methods are used to produce sheet parts. At the same time, the quality of manufacturing of parts, primarily the accuracy of shape, geometric dimensions, perpendicularity of edges, significantly affects the labor intensity of subsequent assembly and welding work, the possibility of their automation and the cost of the vessel as a whole. By improving the quality of cutting, it is possible not only to improve the quality of manufacturing parts, but also to simplify or eliminate such a technological operation as their primary straightening [2].

In the manufacture of offshore drilling platforms and the construction of ships, thermal and mechanical cutting of metal is used. The most effective methods include plasma cutting. This type of thermal cutting makes it possible to obtain steel parts with high quality cut edges in the thickness range of 2...200 mm. In addition to the above objects, such cutting is used to produce parts in many other industries, for example, carriage building, mechanical engineering, and construction.

2. Analysis of literature data and problem statement

The prospects of plasma cutting are associated with the efficiency and economy of using a compressed direct arc [3]. High power concentration (100...150 kW/cm2), the ability to control the process by changing the operating current or plasma gas flow rate over a wide range, as well as the ability to cut almost any metal, provide this method with universal technological capabilities.

The main advantages of plasma cutting of metals include the ability to cut along an arbitrary contour to obtain shaped parts, the absence of mechanical deformations at the cut edges, high productivity, and efficiency [4]. However, this process for manufacturing flat parts has a number of significant disadvantages. These include intensive wear of the non-consumable electrode, the need to use inert gases (for example, to protect the non-consumable electrode from oxidation), defects in the geometry of the cut edges, the formation of areas of increased hardness on the edges and in the heat-affected zone (HAZ), and saturation of the cut edges with nitrogen, which leads to to the porosity of welds during automatic submerged arc welding on metal thicknesses up to 15 mm, restrictions on the thickness of the metal being cut, etc. [5].

One of the ways to minimize (eliminate) such disadvantages is to use air plasma cutting with reverse polarity. This process provides high thermal efficiency as well as high cutting speeds on carbon steels, non-ferrous metals and alloys in an economical process. However, when using traditional plasmatrons with refractory (zirconium or hafnium) inserts in electrodes, this process also has significant disadvantages [6, 7]:

1) limitation on cutting thickness of steel sheets (up to 30 mm);

2) relatively low service life of the electrode, determined by the number of inclusions (approximately 150-200 inclusions);

3) limited current load and power, and, consequently, cutting performance;

4) a decrease in the quality of cut edges with an increase in their thickness.

An effective way to eliminate disadvantages 1-3 is the use of air-plasma cutting at reverse polarity using plasma torches with a hollow electrode [7]. In such plasma torches, the working gas (air) is fed into the hollow electrode with a swirl so that, under the action of the gas vortex and the ponderomotive force, the radial section and the reference spot of the arc deepen into the internal cavity of the electrode, and, rotating, are located in the steady state at a certain distance from its end face. . The magnitude of the arc deepening inside the electrode is determined by the design parameters of the discharge chamber, as well as by the parameters of the plasma torch operation mode. The compression of the plasma arc in such a plasma torch is traditionally carried out by a plasma nozzle.

A separate problem is the elimination of the last, fourth, of the listed shortcomings. Along with the issue of eliminating this drawback, it is advisable to consider searching for opportunities to improve the geometry of the cut edges, reducing the size of the HAZ on the edges and reducing their saturation with nitrogen. As an analysis of the literature on this issue has shown (for example, works [8, 9]), a certain effect in this regard can be achieved by using a water environment during plasma cutting, but this issue requires more detailed study.

3. Purpose and objectives of the study

The purpose of this work is to improve the quality of air-plasma cutting at reverse polarity, which is expressed in minimizing the nonlinearity and taper of the cut, the size of the zone of increased hardness, reducing the surface roughness of the cut edges, and eliminating the formation of flash.

To achieve this goal, the following tasks were solved:

1) Modernization of the design of a plasma torch for air-plasma cutting with reverse current polarity, allowing the use of plasma-forming gas-water (air-water) mixtures.

2) Conducting comparative studies of the quality of cut edges of carbon steel produced by air and air-water plasma cutting on reverse polarity, according to the criteria: non-perpendicularity of the cut edges, their roughness, characteristics of the zone of increased hardness, the content of gas impurities in the edges.

3) Conducting mechanical tests for fatigue resistance to predict the value of fatigue resistance of cut parts and structures made from them that have free (not machined or welded) edges.

4) Determination of trends in the influence of the main parameters of air-water plasma cutting with reverse polarity on the quality characteristics of cutting edges of carbon steel sheets in the thickness range of 2...200 mm.

4. Modernization of equipment and experiments on gas and gas-water plasma cutting of carbon steel.

During the operation of the plasma torch, one of the ways to improve the conditions for converting electrical energy into thermal energy is the introduction of hydrogen into the composition of the plasma-forming medium. One of the ways of its introduction may be the supply of water to the plasma-forming gas. The metered supply of water can be carried out both in the form of steam and directly in liquid form. To implement the latter option, a modification of the plasma torch operating on the reverse polarity of the current was performed. The design of the plasma torch with a copper hollow electrode 1 and a plasma nozzle 2 was supplemented with an external nozzle 3, through which a swirling water flow from the plasma torch cooling system is introduced into the arc column (Fig. 1).

Water is supplied inside the nozzle channel 3 with a clockwise swirl, i.e. in the same direction as the vortex of the gas supplied to the nozzle 1. The water entering concentrically to the plasma column partially evaporates and creates a water vapor curtain around the plasma jet, limiting the access of atmospheric air to the cutting zone. The gases generated during the cutting process are partially precipitated by water.

The kinetics of physical and chemical processes occurring in the arc discharge plasma and at the exit from the plasma torch has a number of specific features. First of all, chemical reactions in the plasma jet occur and mainly end in a relatively small section of the channel of the external nozzle of the plasmatron. The rate of plasma-chemical reactions depends on the nature of the gas flow in the plasmatron nozzle. The nature of the flow affects the value of the transfer coefficient in the plasma jet (diffusion, viscosity and thermal conductivity coefficients), the energy in the gas flow and the jet configuration, the dissociation rate, the movement of liquid droplets in the gas jet, as well as the speed and degree of its fragmentation.

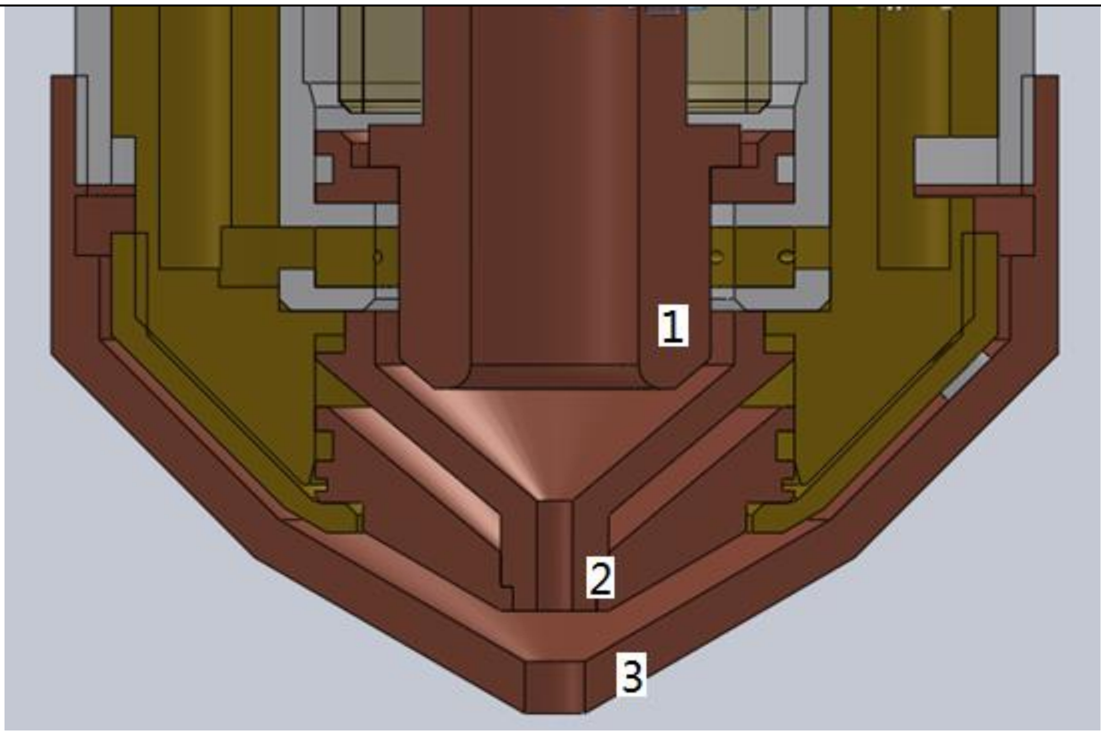


Fig.1. Scheme of a modernized plasma torch with a hollow copper electrode for air plasma cutting on reverse current polarity with the addition of water: 1 – hollow copper electrode; 2 – internal plasma-forming nozzle; 3 – external nozzle for water supply.

To conduct technological experiments on plasma cutting, low-carbon steel plates with a thickness of 16 mm were used, as well as a set of plates with a thickness range of 2...200 mm. Using a modified plasma torch, comparative studies were carried out on the effect of adding water and hydrocarbons to the plasma-forming gas (air) on the gas content in the surface layers of the cut edges. To do this, using the same technological parameters, four variants of cuts were made, with a change in the plasma-forming medium in each case (Table 1). The dependence of the plasma arc voltage on the composition of the plasma-forming medium has been established.

Table 1.

Technological parameters of plasma cutting with reverse current polarity (process speed 120 m/h).

No	Plasma-forming medium	Operating current, A	Arc voltage, V
1.	Air	290	130
2.	Air + water	290	170
3.	Air + propane-butane	290	170
4.	Air + propane-butane + water	290	170
5.	Oxygen + water	290	170

After conducting plasma cutting experiments in the indicated modes, the quality characteristics of the resulting cut edges were assessed. To do this, the non-perpendicularity of the cut edges was determined by visual inspection and measurements, their roughness was determined by taking profilograms, the size of the zone of increased hardness was determined using metallographic and microdurometric methods, and the content of gas impurities in the edges was determined by chemical analysis.

5. Results of studies of gas and gas-water plasma cutting of carbon steel.

The experiments showed that adding 0.028...0.11 l/min of water to the plasma made it possible to improve the quality of the cut edges and reduce their non-perpendicularity. The cut surface had a silver color and a slight roughness of the edge surface (Fig. 2) [10].

a)

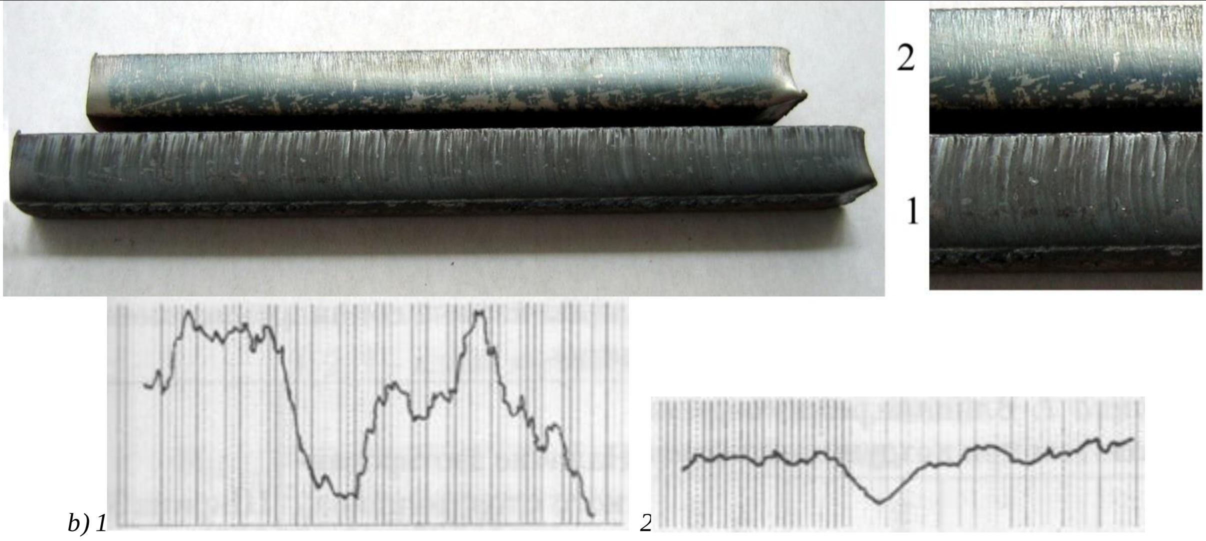


Fig.2. Appearance (a) and roughness profiles (b) of the surface of the edges of low-carbon steel workpieces after plasma cutting; plasma-forming medium: 1 – air; 2 – air + water [10].

It has been established that adding water to the plasma flow from 0.028 to 0.11 l/min (5.6...19.2% steam in the plasma) during plasma cutting with reverse polarity reduces the non-perpendicularity of the cut edges from 2.3...2.5 mm to ≤1.0 mm, which corresponds to the second class according to GOST 14792-80.

In addition, it was found that the magnitude of non-perpendicularity is not stable under the same conditions and depends on the shape of the plasma column. In case of poor-quality machining of the nozzle, misalignment of the nozzle and the cathode insert of the electrode, the shape of the plasma jet differs from cylindrical and when cutting along different coordinate axes, the shape of the cut is different. Therefore, special attention must be paid to the processing and cleanliness of the nozzle.

The cut surface roughness was determined by measuring the standard parameters Rz and Ra using a model 252 profilometer [11]. To measure the surface roughness of the cut edges, samples of 20 × 20 × 8 mm were made. The base length according to GOST 14792-80 was taken to be a distance of 8 mm. During the studies, the speed of movement of the sensor was 300 mm/min, the speed of movement of the tape was 60 mm/min, and the vertical magnification was 5×100. The profilogram and appearance of the edge surfaces are shown in Fig. 2, and the results of roughness measurements are given in Table 2. Data on the HAZ value obtained from metallographic studies and data on microhardness from microdurometric studies are also presented there. For comparison, data on the condition of the edges after oxygen-acetylene cutting and mechanical polishing are presented [12].

Table 2.

Dependence of the roughness and microhardness of the metal at the cut edge on the cutting method.

No	Cutting method	Roughness, R_z, μm	Microhardness HV at a load of 20 g, MPa	HAZ size, mm	Quality class GOST 14792-80	Cutting speed, m/h
1	Acetylene-oxygen	100…120	2350…2700	1,2-2,0	3	27
2	Plasma, plasma-forming medium – air	80…100	6510…8610	0,6	2	120
3	Plasma-forming medium – air+water	10…20	3060…3660	0,46	1	120
4	Mechanical restoration (polishing)	5…10	1500…1700	–	–	–

From each of the cutting surfaces (in the second third of the sample length), as well as from the base metal, 90 samples measuring 3 × 3 × 2 mm were cut mechanically without significant heating. Chemical analysis of the oxygen, nitrogen and hydrogen content in the cut samples was carried out using the reduction melting method in a gas carrier flow. Its results are shown in Table 3.

Table 3.

Results of chemical analysis of the presence of gas impurities in the metal of the cut edges.

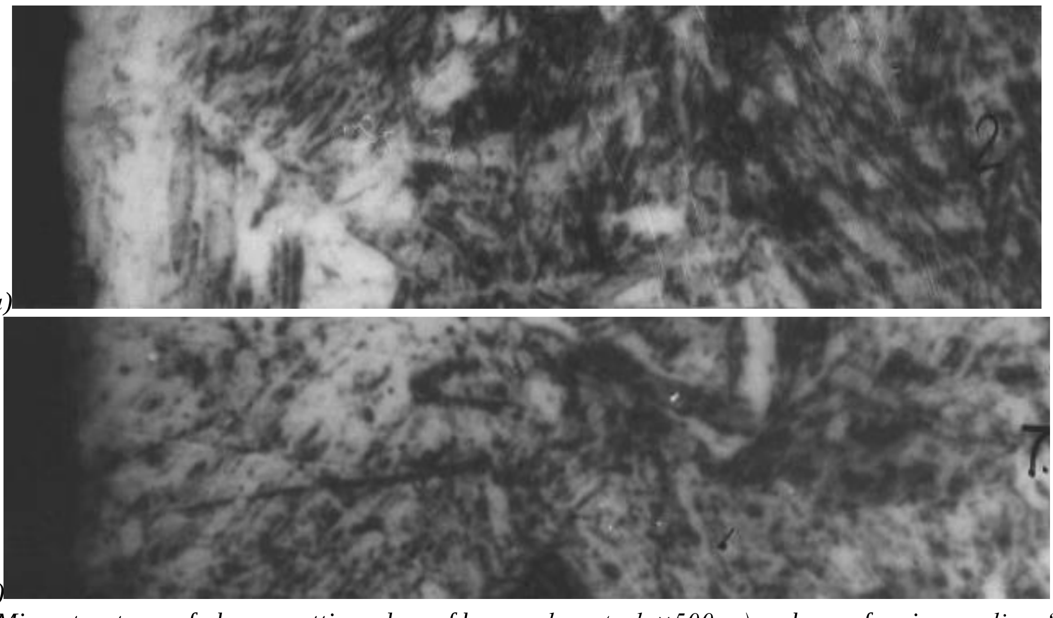
No	Material	Gas content, wt.%		
		O	N	H
1.	Metal from the cut surface, plasma-forming gas - “air”	0,06	0,046	0,001
2.	Metal from the cut surface, plasma gas "air + water"	0,02285	0,0092	0,0008
3.	Metal from the cut surface, plasma gas "air + propane-butane"	0,0171	0,013	0,0006
4.	Metal from the cut surface, plasma gas “air + water + propane-butane”	0,0152	0,0145	0,0006
5.	Base metal	0,0075	0,006	0,0011

Metallographic studies have shown that in all considered cases of plasma cutting there is a heat-affected zone on the cut edges. Microdurometric analysis showed heterogeneity of HAZ hardness. In the near-surface layer of the cut edges, there is an increase in microhardness compared to the microhardness of the HAZ and base metal (Table 4). The greatest increase in microhardness is observed when air is used as a plasma-forming medium. Chemical analysis showed that this is due to the saturation of the edges with nitrogen during the air plasma cutting process, as well as the high rate of their cooling. In this case, in the case of using air as a plasma-forming medium, a continuous white solid layer up to 0.02 mm deep is observed on the edges (Fig. 3, a). When using a mixture of “air + water”, such a layer is absent (Fig. 3, b).

Table 4.

Influence of the composition of the plasma-forming medium during plasma cutting with reverse current polarity of carbon steel on the distribution of microhardness in the HAZ and the depth of the nitrided layer.

№	Plasma-forming medium	Depth of nitrided layer, mm	HAZ, mm	Distribution of microhardness HV from the cut surface deep into the HAZ (load 20 g), MPa
1	Air	Solid white layer 0,007…0,02	0,6…0,65	6000, 4730, 3620, 3210, 2100
2	Air	0,016	0,5…0,65	7000, 4700, 3000, 2700
3	Air + water	Not visible	0,46…0,5	5200, 4120, 3820, 3210, 2560, 2300
4	Oxygen + water	Not visible	0,4…0,46	4500, 3620, 3210, 2570, 2300



a)
b)

Fig.3. Microstructures of plasma cutting edges of low-carbon steel, ×500: a) – plasma-forming medium “air”; b) – plasma-forming medium “air + water”.

The condition of the surface of the cut edges can affect the fatigue resistance of cut parts and structures made from them that have free (not processed after plasma cutting) edges. To assess the influence of the thermal cutting method in the manufacture of parts on their fatigue resistance, comparative tests of flat samples made of D32 shipbuilding steel 10 mm thick for alternating bending were carried out. The tests were carried out in air, based on 107 cycles [12]. Based on the test results, fatigue curves were constructed for samples manufactured by oxy-acetylene cutting and plasma cutting in a plasma-forming environment “air + water” (Fig. 4) [13].

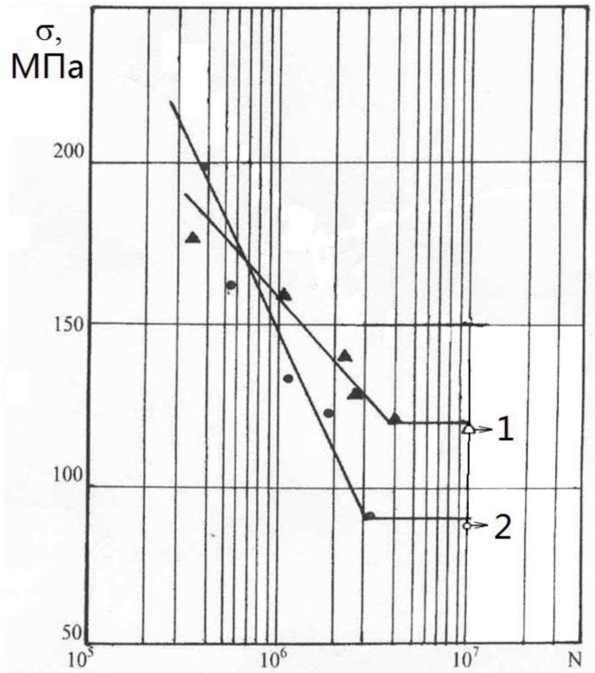


Fig.4. Fatigue curves of samples made of shipbuilding steel of category D32, manufactured by air-plasma cutting with the addition of water (1) and oxygen-acetylene cutting (2) [13].

6. Discussion of the results of gas and gas-water plasma cutting of carbon steel.

Two factors contribute to reducing the non-perpendicularity of the cut edges: the formation of gas mixtures with hydrogen, which increases the electric field strength of the arc, and compression of the plasma arc. When water or hydrocarbons (propane-butane) are added to the plasma-forming air, the arc voltage increases by 25...30 V at a constant current value. Compression of the arc increases its energy characteristics and contributes to the immersion of the anode spot throughout the thickness of the metal. This is evidenced by an increase in the width of the cut at the lower edge of the cut. The non-perpendicularity of cut edges of different thicknesses is reduced by approximately 2-2.5 times.

Change in the total water flow into the plasma torch nozzle (1.67...3.3) 10–3 l/s when cutting in a plasma-forming medium “oxygen + water” and (1.67…4.67) 10–3 l/s when cutting in an “air + water” environment, the non-perpendicularity of the cut edges practically does not change. An increase in the flow rate of the plasma-forming medium without changing the water flow rate leads to a decrease in the non-perpendicularity of the edges for the “air + water” medium from 1.3 to 0.83 mm; “oxygen + water” – from 1.5 to 0.65 mm.

A study of profilograms and the appearance of cut edge surfaces showed that air plasma cutting with the addition of water provides the lowest roughness. In this case, the cut surface is smooth, silver in color, the protrusions and depressions have smooth transitions. The value of Rz is 10...20 µm, Ra ~ 2.23 µm. These indicators correspond to quality class 1 according to GOST 14792-80. Air plasma cutting without adding water provides quality class 2 Rz – 80...100 microns.

Studies of the chemical composition of cut edges have shown that the addition of water to the plasma-forming gas (air) during air-plasma cutting at reverse polarity makes it possible to reduce the nitrogen content in the surface areas of the edges by more than 5 times, which brings them closer to the base metal in this parameter. The oxygen and hydrogen content also decreases. This makes it possible to weld workpieces cut in this way directly after plasma cutting without mechanical processing of the edges or with its minimal use, which provides a significant economic effect while simultaneously reducing the construction time of marine engineering facilities and ships.

It should be noted that when plasma cutting using a two-component plasma-forming mixture “air + propane-butane”, gas saturation of the cut edges is practically identical to such saturation during air plasma cutting with the addition of water. But at the same time, a slightly higher nitrogen content is observed in the surface layers of the cut, which can lead to porosity of welds made directly along the cut edges (without additional mechanical processing).

Studies of samples of low-alloy steel of category D32 for fatigue resistance showed that samples cut by air-plasma cutting with the addition of water have an endurance limit of at least 120 MPa, which is 33% higher than samples cut by oxy-acetylene cutting, the endurance limit of which was 90 MPa (Fig. 4).

Technological studies have shown that when using air-water cutting with reverse current polarity, it is possible to cut steel sheets with a thickness of 2...200 mm. The geometric parameters of the plasma torch have the greatest influence on the width of the cut. Thus, when the radius of the plasma-forming nozzle increases from 1.5 to 3 mm, the cross-sectional width of the cutting cavity increases from 2.75 to 3.80 mm, which is ~38%. With other plasma cutting parameters remaining unchanged, an increase in operating current from 200 to 400 A leads to an increase in the width of the cut cavity by 12%, while an increase in the flow rate of plasma-forming gas or a gas mixture (for example, air-water) from 5 to 8 m3/h leads to a decrease transverse dimensions of the cutting cavity by 6%. The average width of the cutting cavity is also slightly influenced by the length of the external nozzle of the plasma torch, changing which leads to changes in the width of the cutting cavity within 4...5%.

7. Conclusions.

1. To obtain the possibility of using both air and air-water plasma-forming media for air-plasma cutting with reverse current polarity, it is proposed to use an additional external nozzle with a swirler in the plasmatron, through which water is introduced into the arc column at a flow rate of up to 20% of the air flow rate.

2. Replacing the air plasma-forming medium with an air-water mixture during reverse polarity plasma cutting of carbon steel in the thickness range of 2...200 mm allowed:

- reduce the non-perpendicularity of the cut edges by 2-2.5 times;
- reduce the roughness of the cut edges from Rz 80...100 μm to Rz 10...20 μm;
- reduce the size of the HAZ by 20...30%;
- reduce the microhardness of the HAZ by more than 2 times;
- reduce the content of oxygen impurities in the cutting edges by 2.6 times, hydrogen – by 20...25%;
- eliminate the nitrided layer on the cut edges.

3. Mechanical tests of cut samples for fatigue resistance showed that the use of an air-water mixture for reverse polarity cutting increases the endurance limit by 33%.

4. The following trends have been established for the influence of the main parameters of air-water plasma cutting in reverse polarity on the change in the cutting width of carbon steel sheets in the thickness range of 2...200 mm: reducing the radius of the plasma-forming nozzle from 3 to 1.5 mm leads to a decrease in the cutting width by ~38 %; increasing the operating current from 200 to 400 A – increasing the cutting width by 12%; An increase in the flow rate of the air-water mixture from 5 to 8 m3/h leads to a reduction in cutting width by 6%.

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