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Influence of Plasma Torch Design on Cutting Quality during Precision Air-Plasma Cutting of Metal

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Abstract—Optical interferometry and metallographic analysis were used to study the structure of cutting seams obtained after 09G2S steel cutting by a PMVR-5 plasma torch. These plasma torches have many design features in the gas-dynamic stabilization system of the plasma arc. The application of a new plasma torch can obtain higher quality and lower energy costs of cutting medium-thick 09G2S steel. Metallographic analysis has shown that the qualitative composition of the cut surface structure is almost the same, so priority criteria for comparative quality analysis are surface microgeometry parameters. The parameter evaluation shows high quality of cutting almost along the entire length of a cut, since the technological feature influence of plasma arc cut into the metal affects less than 0.3 mm from the sheet edge. The use of additional methods of gas-dynamic stabilization in PMVR-5.2 plasma torch (feed symmetry with a double swirl system of plasma-forming gas) makes it possible to achieve additional advantages in terms of surface quality compared to PMVR-5.1. A number of features that affects cut quality when cutting metals of different thicknesses for welding depends on the inclination angle of a plasma torch during cutting. Estimates of the surface layer hardness indicate minimal deviations from the requirements of GAZPROM Standard 2-2.4-083 (instructions on welding technologies in the construction and repair of field and main gas pipelines), which allows further use of cutting seams obtained by studied plasma torches for welding without removing thermal influence zones. Thus, the application of new plasma torches for precision-finishing plasma cutting of metals, including production of welded joints, is possible.

Keywords: plasma torch, design, welding seems, heat-affected zone, structure transformation, defects, quality, efficiency

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INTRODUCTION

The development of modern engineering and a number of other technology branches is largely determined by technologies and methods of processing construction steels. Particular attention is paid to the development of effective methods for cutting of sheet steels for subsequent welding of critical metal structures [1, 2]. It should be noted that the existing traditional processes of material separation based on mechanical and physico-mechanical effects have a number of significant drawbacks due to the very low productivity and unlikelihood of cutting sheet steels of different thicknesses along a complex curved contour [3]. Plasma cutting methods are currently considered very promising [4], in particular using the technology of air-plasma processing of metals [5–7]. However, considering all the advantages of plasma cutting technology [8–10], the cutting process of sheet steel is often accompanied by various deviations in the cutting surface quality, which substantially depend on the processing conditions [11–13] and on the design of the plasma torch itself [14, 15].

FORMULATION OF THE PROBLEM

A comparative analysis of the plasma cutting effectiveness of metal materials depending on plasma torch design features showed that, even under normal processing conditions, the structure formation of the cut

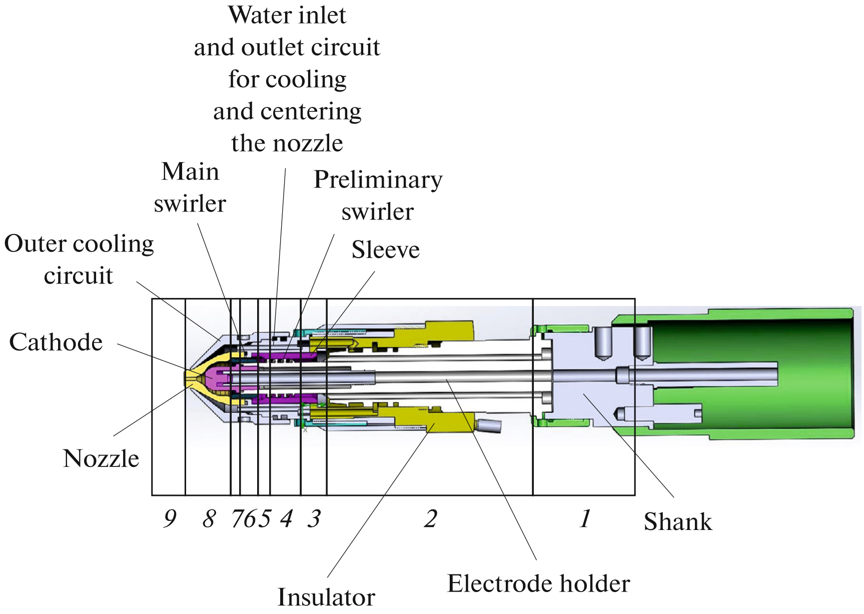

Fig. 1. Design diagram of PMVR-5.2 plasma torch with two swirlers in gas-vortex stabilization system: (*1*) gas inlet section; (*2*) channels for PFG supplying to the zone of preparation and alignment of PFG flow (sections *3*–*6*); (*3*) expansion chamber for flows mixing (MC); (*4*) preliminary (forming) swirler (FS); (*5*) second expansion chamber; (*6*) second stabilizing swirl (SS); (*7*, *8*) nozzle unit; (*9*) free plasma arc zone.

surface is largely determined by the features of electric arc units and gas-air ducts (GAD) of cutting plasma torches [16]. At the same time, among the developments of domestic electroplasma equipment, there are barely any instrumental plasma torches for precision cutting of steel sheets with rolled thickness up to 40 mm that can provide increased accuracy and quality of edge cutting, high material and energy efficiency. To solve such problems, the simulation results of gas-dynamic and thermophysical processes determined the design effect of the gas-air duct of the plasma torch on the plasma-forming gas (PFG) flow, which made it possible to develop and fabricate a modernized plasma torch with additional compression of the plasma arc, as well as improve characteristics for most of the cut quality parameters [17].

One of the significant conditions affecting the plasma cutting quality is the efficiency of the gas-vortex stabilization (GVS) system in plasma torches for air-plasma processing of metals [18]. As a criterion for the effectiveness of GVS, the distribution uniformity degree of PFG flow parameters in the control sections (primarily in the cylindrical channel of the nozzle assembly) of the plasma torch's gas-air duct can be used.

RESEARCH METHODS

PMVR-5.1 and PMVR-5.2 plasma torches, which were developed and fabricated at Scientific Production Association Polygon Ltd. (Yekaterinburg) for metal cutting, were used as study models. Plasma torches of this type refer to the PMVR-5 series of single-flow plasma torches with an integrated step-by-step gas-dynamic filter and increased performance for operation at currents up to 200 A. In comparison with the widely used PMVR-M plasma torch, their designs have a modernized system for preparing and equalizing the PFG flow before the entry into the nozzle block. Such a system includes the following (sequentially): an expansion chamber, a preliminary (forming) swirler, a second expansion chamber, and a main (stabilizing) swirler. The difference between the plasma torch PMVR-5.2 (Fig. 1) and PMVR-5.1 is in the manner of how PFG is fed into the expansion chamber. It is known that the PFG feed asymmetry to the expansion (soothing) chamber is one of the main reasons for the low GVS efficiency, which is observed in most plasma torches with a single-flow GAD scheme. In order to minimize the effect of this factor in the PMVR-5.2 plasma torch, the PFG is fed into the preliminary swirler through two holes located symmetrically with respect to the axis of the plasma torch, and in PMVR-5.1—through one asymmetric hole.

The gas inlet section in the forming swirler (FS), in addition to the flow distribution function over the channels, also acts as a reflector, providing the formation of the reverse gas circulation zones in the ring channel of the mixing chamber (MC). After interacting with the gas inlet wall in FS, the gas flow partially changes the motion direction to the radial one dissipating the kinetic energy and increasing the vortex intensity within MC. The mixing chamber sizes at the section *3* GAD were selected as a result of the compu-

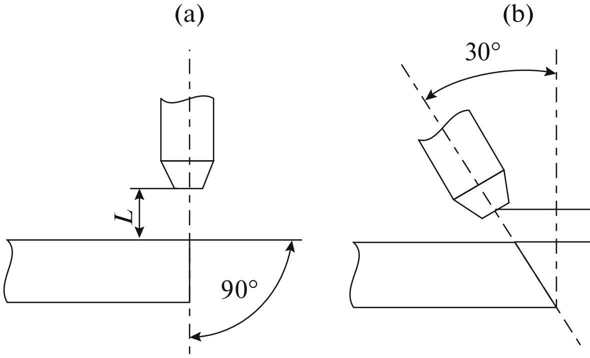

Fig. 2. Scheme of control plates cutting at angle of 90° (a) and 30° (b).

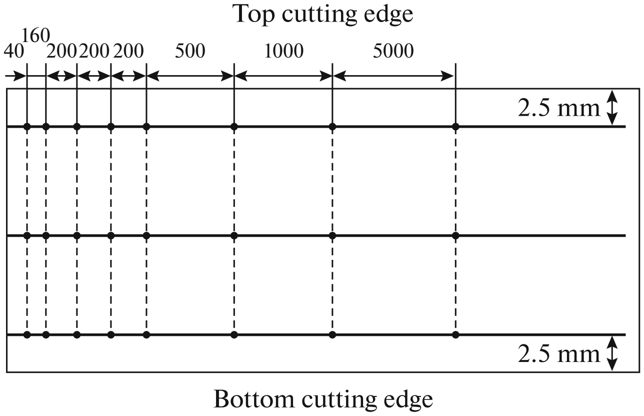

Fig. 3. Arrangement of points for measuring the hardness of thermal influence zone of the cutting edge.

tational optimization procedures for generally accepted design considerations for plasma torches of this type [19]. The FS has four inlet gas channels and is located at a distance of 4 to 5 calibers (13 to 16 mm) from the inlet point of the PFG to the mixing chamber. Such a swirler is preliminary and performs the function of giving the PFG flow a direction that matches the rotation direction of the second main swirler (section *6*). The FS location choice was made in accordance with previous estimates for the PMVR-5.1 (2M) plasma torch [17]. The nozzle unit is made of standard commercially available nozzle and cathode pairs.

The quality studies of plasma cutting were carried out on flat plates made of 09G2S steel with a thickness of 14 mm at different inclination angles of the plasma torch according to the scheme shown in Fig. 2. The cutting modes are shown in Table 1.

Depending on the plasma torch design, the microstructure analysis of the samples after plasma cutting was carried out using a Neofot microscope at magnifications of 100 to 160 times. The steel microstructure was identified according to GOST 8233–56 on preprepared thin cross sections after etching in a 4% solution of nitric acid in ethanol.

Hardness surface measurements adjacent to the metal cutting edge were carried out on a LEICA instrument with the Materials Workstation software at loads of 1000 g. The measurement scheme is shown in Fig. 3 and the results are presented in Table 2.

EXPERIMENTAL RESULTS

The calculations showed that when PFG is fed into the preliminary swirler of the plasma torch (PMVR-5.2) through two holes symmetrically located relative to the axis of the hole compared to a plasma torch (PMVR-5.1) with one asymmetric hole, the degree of compression of the plasma jet increases by almost 20%. Such an increase in the precision (Table 1) of narrow-jet plasma had a positive effect on the steel's cutting mode under study, which made it possible to increase the sheet's cutting speed, thus resulting in process productivity on average by 15%, regardless of the material processing scheme. The experimental values of the typical parameter increase of the plasma-forming arc are also important to note when performing an oblique cut with a plasma torch at an inclination angle of 30°, which is due to the increase in the cut

Table 1. Cutting modes for samples *4* and *5*

Parameter	Parameter value for plasma torch			
	PMVR-5.1 (sample *1*)		PMVR-5.2 (sample *2*)	
	1.1. Oblique cut	1.2. Straight cut	1.1. Oblique cut	1.2. Straight cut
Arc current, A	115	88	115	88
Arc voltage, V	200	180	200	180
Cutting rate, m/min	1.10	0.65	1.25	0.75
Nozzle diameter, mm	1.7	1.7	1.7	1.7
Distance to nozzle exit *L*, mm	5	5	5	5
PFG pressure, MPa	0.5	0.5	0.5	0.5

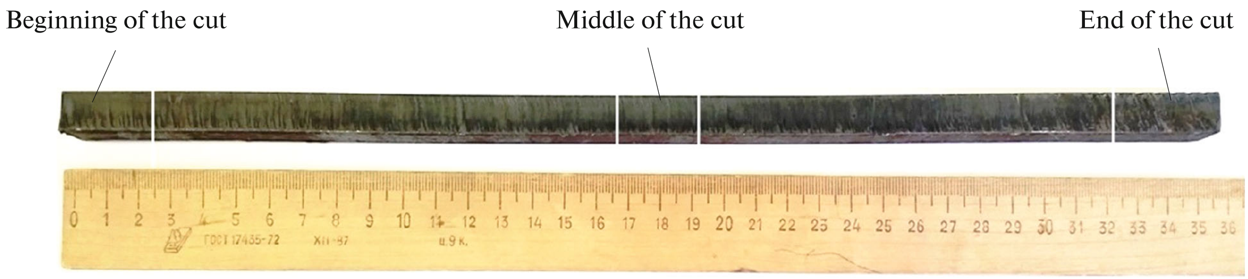

Fig. 4. Appearance of the sample after direct plasma cutting of steel sheet by PMVR-5.1 plasma torch and template cutting scheme.

length over the thickness at the considered steel cutting pattern.

The visual analysis of the samples subjected to plasma cutting according to the selected modes made it possible to determine the degree of the surface cleanliness and the geometry of the cut edges when using the considered plasma torches. The design features of the PFG feed in different models of the studied plasma torches did not lead to significant differences in the macro picture of the cut surface state. The external control showed (Fig. 4) that almost no formation of burr and sticking of molten metal drops were detected on lower edges all studied samples. In addition, no melting and rounding of the upper edge were detected, which ensured an almost zero cut deviation. It was found on cut templates that the surface quality itself along the cut length is largely determined by the distance from the place where the plasma jet started cutting into the sheet end.

Table 2. Results of HV1 hardness measurement

The distance from the surface, µm	Hardness HV_1 of samples		
	3.2	*1.1*	*2.2*
40	364	380	355
160	246	210	313
200	210	196	228
200	205	197	206
200	198	208	202
500	201	201	196
1000	202	193	187
5000	196	206	186

Table 3 shows the results of microgeometry measurements of the cut surface at different sections along the length of the cutting seam. The surface roughness was studied using a Veeco optical interferometer in different-sized areas of the relief. In the place of the plasma jet cutting into metal, the cut surface has the maximum mean roughness (*Ra*) and maximum height (*Rz*) of the profile. These indicators increase significantly with an increase in the studied surface area, which characterizes the extreme irregularity of the microrelief.

At the beginning of the cut, when the plasma torch operating mode has not yet reached adjustable stable parameters, the edges of the upper furrows are melted due to surges in current and low cut rate, and the average height from the hollow to the top increases, which contributes to the increase in the interval of furrows and the significant roughness appearance of the cut surface (Fig. 5a).

However, the plasma cutting mode is stabilized and reaches the set values for all given parameters until the end of processing already at a distance of 0.25–0.30 mm from the edge. As a result, the cut surface topogram along the entire length becomes almost the same with a sharp decrease in the normalized indices (Fig. 5b). In this regard, for all subsequent studies, the templates were cut from the middle part of the steel strip under study.

A comparative comparison of all studied samples using the quantitative metallography methods showed that, regardless of the cutting mode and plasma torch type, the microstructure was almost the same, and the thickness of the plasma cutting's outer zone was 400 µm, and the thickness of the heat-affected zone did not exceed 100 µm (Fig. 6).

Table 3. Surface study results of different sections along the length of steel sheet

Template cutting scheme (sample number)	*Ra*, µm, for		*Rz*, µm, for	
	small section	large section	small section	large section
Beginning of the cut (3.1)	7.34	43.94	41.75	245.87
Middle of the cut (3.2)	2.78	5.62	21.22	89.63
End of the cut (3.3)	3.45	6.66	25.81	67.28

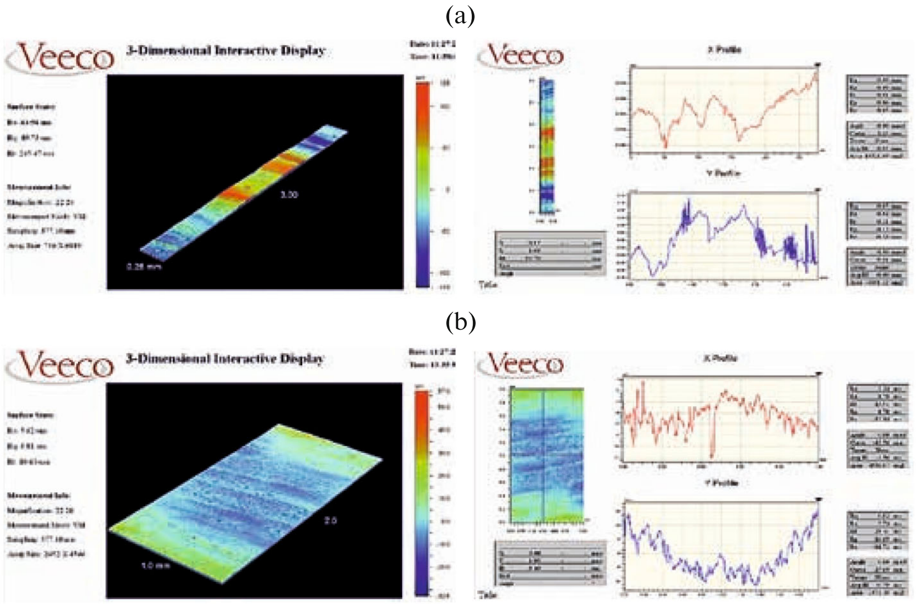

Fig. 5. Topography of cut surface for the sample 3.1 (a) and 3.2 (b) (large section).

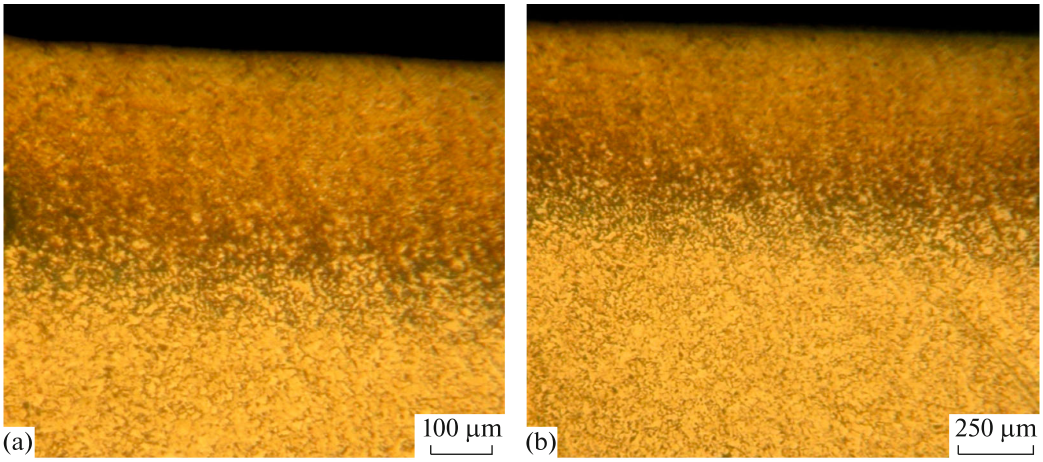

Fig. 6. Microstructure of the samples after plasma cutting.

By structure, the plasma cutting zone is a hidden plate pearlite 2 points with a shallow-plate distance of approximately 0.30 µm. The heat-affected zone has a pearlite-ferrite structure with a number ratio of these phases of 75/25. The base also has a pearlite-ferrite structure with an above-phase ratio of 20/80.

It can be seen in Table 2 that the near-surface zone hardness does not exceed 380 HV1 along the entire cut surface, with structural regions prevailing for all samples, only slightly differing in hardness from the base material.

Table 4 presents the study results of the surface microrelief of the samples obtained as a result of

Table 4. Results of the cutting surface study depending on plasma torch design

Plasma torch type	Sample	Beginning of the cut	*Ra*, µm, for		*Rz*, µm, for	
			small section	large section	small section	large section
PMVR-5.1	1.1	Straight cut	11.16	74.27	117.69	185.01
	1.2	Oblique cut	9.67	62.35	112.63	152.56
PMVR-5.2	2.1	Straight cut	4.98	55.73	43.82	93.13
	2.2	Oblique cut	3.70	23.82	9.21	74.65

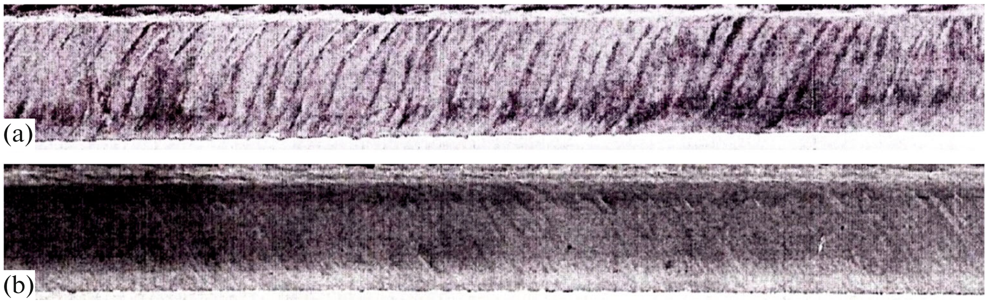

Fig. 7. Appearance of cutting surface depending on inclination angle of plasma torch: (a) straight cut (sample 2.1); (b) oblique cut (sample 2.2).

plasma cutting a steel sheet according to the modes (Table 1).

DISCUSSION

Summarizing the results of complex microstructural studies, the structure's qualitative composition within the considered limits of the technological and design parameters of the tests almost does not change. Therefore, as shown in [20], it is advisable to estimate the cut quality by the criterion of the surface microgeometry.

It can be seen from Table 3 that the best performance in the microgeometry study of the cut surface was obtained using a plasma torch PMVR-5.2 with two PFG feed holes into the preliminary swirler that was symmetrically positioned with respect to the plasma torch axis. It should be noted (Fig. 7) that a similar design feature affected the cut quality with the plasma torch at an inclination angle of 30°.

Analyzing the presented results, we can conclude that they meet modern domestic and foreign requirements for the quality of cutting [21–23], which makes it possible to expand the application scope of plasma-arc technologies in a wide range of relevant industries.

CONCLUSIONS

The application of new GVS methods in PMVR-5.1 and PMVR-5.2 plasma torches makes it possible to obtain precision cuts corresponding to the first quality class according to GOST 14792–80 for 09G2S grade steel of medium thickness. The qualitative composition of the cut surface structure is almost the same. Therefore, the surface microgeometry characteristics become a priority criterion for the comparative quality analysis. It should be noted that the estimate by this parameter shows a high quality of cutting along almost the entire cut length, since the effect of a plasma arc's technological features cut into a metal affects the distance of less than 0.3 mm from the sheet edge. The use of additional methods of gas-dynamic stabilization in the PMVR-5.2 plasma torch (feed symmetry with a double PFG swirl system) can achieve additional benefits in terms of the surface quality in comparison with the PMVR-5.1 plasma torch. Hardness estimates of the surface layer indicate the minimal (at depths on the order of 40 μm) deviations from the requirements (≤300 HV) of Gazprom Standard 2-2.2-136–2007, which makes it possible to use the cutting seams obtained by the studied plasma torches for welding without removing heat effect zones in the future. The introduction of modern plasma cutting technologies makes them more competitive in terms of efficiency, quality and a number of other significant criteria.

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