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Qualitative Study of Steel Cutting with the Use of the Narrow Jet Plasma Technology

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Abstract—By metallography and optical interferometry methods, the structure of 09G2S steel cutting seams fabricated with the use of narrow jet plasma technology is analyzed. The high quality of the seams allows welding without the removal of the heat-affected zones. The application of the new narrow jet plasma cutting technology provides high-quality welding seams, high efficiency of the process, and low energy consumption.

Keywords: plasmatron, plasma cutting of steel, cutting quality, heat-affected zone, structural transformation

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INTRODUCTION

Plasma cutting of metals is one of the most demanded technologies in metallurgy and machine engineering. Among the latest achievements in this sphere, one can note the so-called precise, compressed, or narrow jet plasma [1], which significantly exceeds the traditional plasma cutting techniques for metals of small and medium thickness in terms of efficiency and material and energy consumption and is comparable to laser metal cutting in terms of the cutting width and quality [2]. Unfortunately, in spite of the existing theoretical developments of similar technologies in Russian engineering [3], only the products of foreign producers are currently available in the market (Hyperterm, Kjellberg, Messer Greisheim).

On the basis of the results of the long-term studies and the experience of the design of plasma torches of different application [4–6], several modifications of a narrow jet plasma torch PMVR-5 for metal cutting using new arc stabilization systems were developed, which should contribute to the increase in the heat input efficiency and the corresponding improvement of the metal quality in the cutting area (the decrease in the size and the change in the microstructure of the heat-affected zone (HAZ), the decrease in the roughness, and the improvement of other parameters regulated by the GOST (State Standard) 14792-80) and, thus, the quality of the resulting welds.

In this work, the parameters that characterize the quality of cutting structural low-alloy steel using a PMVR-5 plasma torch were experimentally studied.

EXPERIMENTAL

The distinctive feature of the narrow jet plasma technique is the use of the distributed supply of the plasma-forming gas to a sectioned nozzle, which means that the tangentially swirled plasma-forming gas (PFG) flow of the main channel is additionally surrounded by a secondary gas flow at the plasma torch nozzle outlet. The studies were performed for a PMVR-5.3 plasma torch (Fig. 1), which is a modification of a PMVR-5 narrow jet plasma torch produced by NPO Poligon and OOO TERUS (Russia). By plasma cutting of flat plates made of 09G2S low-alloy structural steel with the thickness of 10 mm with edge grooving at an angle of 90° and 60°, four samples were fabricated, whose geometries are shown in Fig. 2. The operating regimes of cutting are shown in Table 1.

Note that cutting of metal with the thickness of 10 mm using the narrow jet plasma technique is characterized by a significantly lower energy consumption (12.5 kW) and a significantly higher speed (1.1 m/min)

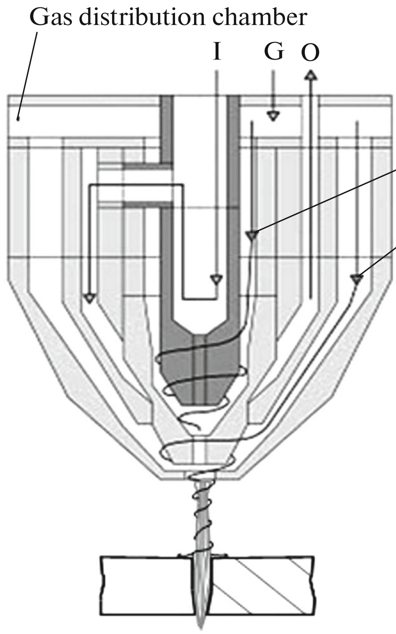

Fig. 1. Scheme of the two-channel gas supply to a PMVR-5.3 narrow jet plasma torch for metal cutting: I and O are the inlet and the outlet of the cooling liquid; G is the plasma-forming gas supply to the gas distribution chamber; G1 is the plasma-forming flow; G2 is the stabilizing flow.

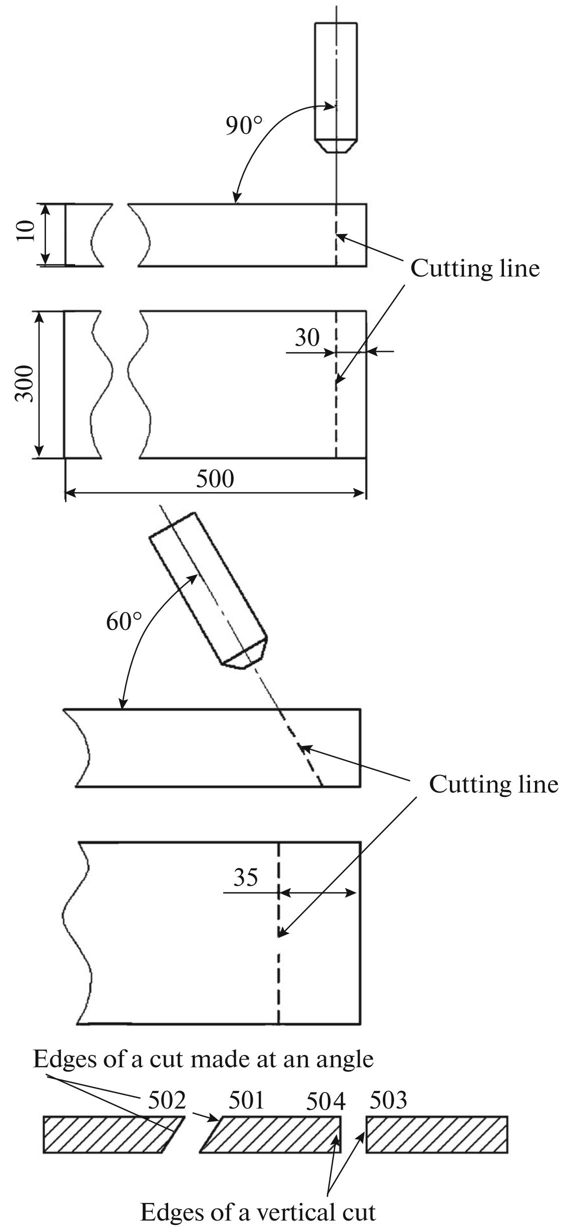

Fig. 2. Samples made by cutting a steel plate at an angle of 90° (nos. 503 and 504) and 60° (nos. 501 and 502).

than when using the traditional plasma torches with the one-channel gas supply (15–20 kW and 0.54 m/min, respectively). As a result, besides the expected improvement of the cutting quality owing to the decreased heat input to the cutting area, a significant increase in the productivity, energy efficiency, and safety of the process is achieved [6].

The surface relief of samples after plasma cutting was studied using a Veeco optical interferometer in the center of a cut. The metallographic structural studies of samples etched in a 4% nitric acid solution in ethyl alcohol were performed using a Neophot 21 microscope at the magnification of ×50–1000. The steel microstructure identification was performed in accordance with GOST (State Standard) 8233-56.

The microhardness of the samples was measured using a Leica Materials Workstation device at the load on an indenter of 1000 g; the scheme of indentation is shown in Fig. 3.

Because 09G2S steel is one of the main materials for the manufacture of pipe rolling, the quality criteria were the parameters established by the STO Gazprom 2-2.4-083 and STO Gazprom 2-2.2-136-2007 standards. In the studied case, such parameters are angles of groove welds after plasma cutting, whose measurement scheme is shown in Fig. 4.

RESULTS AND DISCUSSION

In Table 2, the results of the measurement of the angles of groove welds for experimental samples after plasma cutting are shown. It can be seen that the deviation of perpendicularity is 1°30′ (the shift is $\Delta \leq 0.25$ mm) on one edge of a vertical cut and 5°50′ ($\Delta \leq 0.9$ mm) on the other, which corresponds to the quality classes 1 and 2 in accordance with GOST 14792-80. The angular values of the bevel cuts are also within the tolerance of 5° and correspond to the requirements of STO Gazprom 2-2.2-136-2007.

Table 1. Cutting regimes for samples (P—perpendicular cutting, A—cutting at an angle)

Sample no.	Cutting regime							
	I, A	U, V	cathode	nozzle diameter, mm	cutting speed V, m/min	cutting gap L, mm	PFG	PFG pressure at plasmatron inlet P, MPa
501 (A)	88	142	Copper with a hafnium insert	1.6	1.1	5	air	0.45
502 (A)								
503 (P)	90	138						
504 (P)								

Table 2. Groove weld angles

Sample no.	501	502	503	504
Angle	26°00′–26°30′	25°00′–25°30′	91°10′–91°30′	84°10′–84°40′

The studies of the relief of the cut surface (Fig. 5) showed that the average roughness value is 3–7 μm (Table 3), which corresponds to the quality class 1 in accordance with GOST (State Standard) 14792-80. The maximum roughness values of the studied surfaces are also within the limits for quality class 1 (up to 50 μm).

The microstructure of samples is shown in Fig. 6 and described in Table 4. The HAZ thickness is 500 μm for all samples, which corresponds to quality class 2 in accordance with GOST 14792-80. The comparison with the cut surface made using PMVR-M and PMVR-2M plasma torches with the one-channel supply PFG [7] indicates a significant decrease in the thickness of the overheating zone owing the decrease in heat input and a higher cutting speed of a PMVR-5.3 narrow jet plasma torch.

The HAZ structure in all the studied samples differed from the perlite–ferrite structure of the base steel with the ratio P/F = 5/95–20/80. In samples with a perpendicular cut in HAZ, the thin-plate perlite with the ratio P/F = 85/15 was observed, and in samples with bevel cut, sorbitic perlite with P/F = 65/35–75/25 was observed. Depending on the overheating temperature, two zones are clearly distinguished in HAZ (Table 4): the outer HAZ_1, which was overheated to 900°C during cutting, and HAZ_2 located closer to the base, which was overheated insignificantly (to ~550°C). The formation of perlite in HAZ_1 with the interlamellar spacing of 0.3–0.4 μm indicates the normalization of steel. The increase in the perlite fraction in the HAZ structure compared to the base is associated with the recrystallization and the high cooling

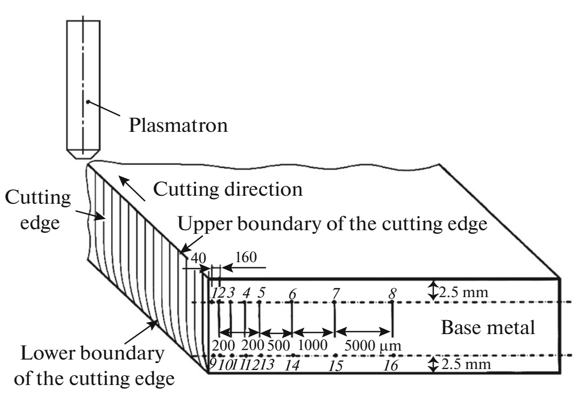

Fig. 3. Scheme of the hardness measurement on the cutting surface.

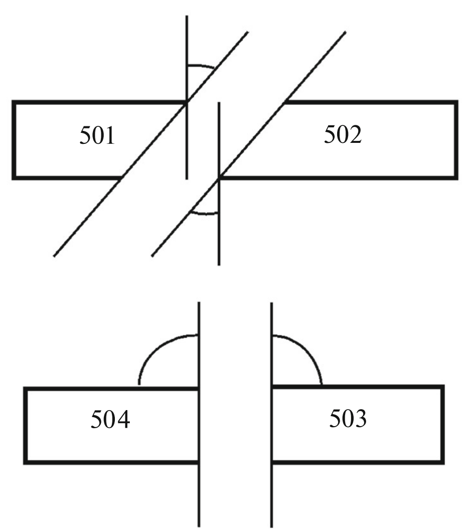

Fig. 4. Scheme of the angle measurement of a groove weld made by plasma cutting.

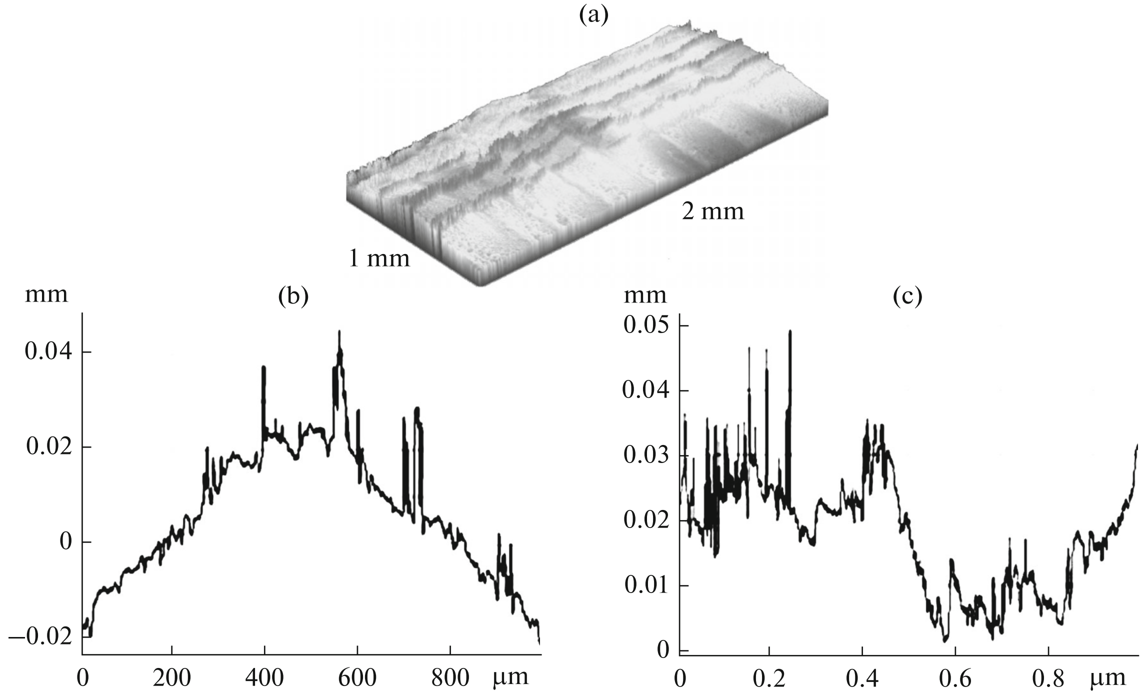

Fig. 5. (a) Relief and (b, c) profilograms of the cutting surface of sample no. 502.

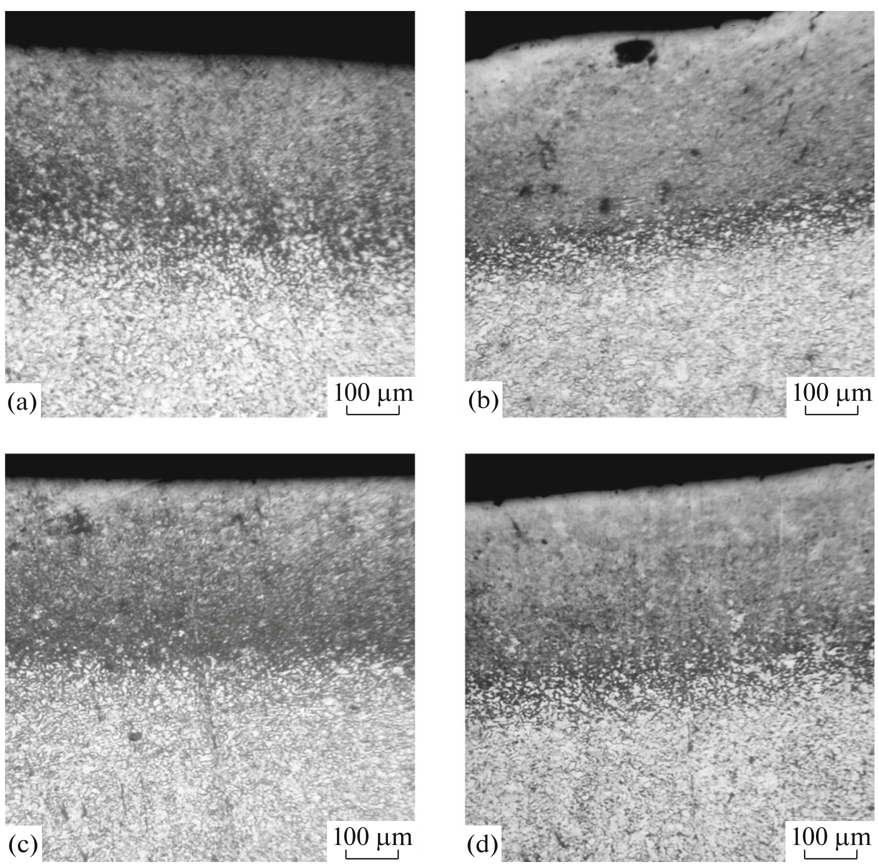

Fig. 6. Microstructure of the surface of samples in the cutting area: (a) sample no. 501; (b) sample no. 502; (c) sample no. 503; (d) sample no. 504.

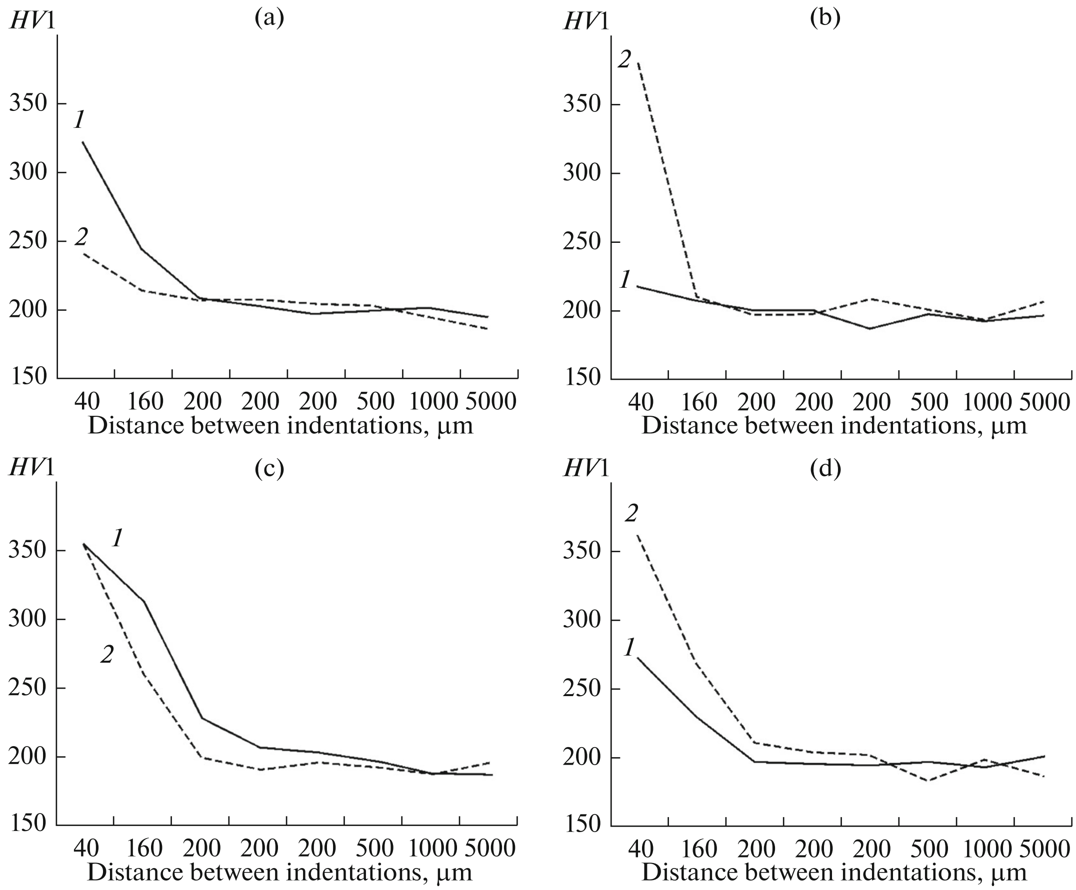

Fig. 7. Hardness distribution along the depth on the cutting surface: (a) sample no. 501; (b) sample no. 502; (c) sample no. 503; (d) sample no. 504. (*1*) Lower cutting edge; (*2*) upper cutting edge.

rates after cutting owing to the heat output through the material and the surface of joined plates.

It is known [8, 9] that the impact strength and the fracture toughness of welds depend on the strength properties of the starting material, for which the presence of granular perlite with the average cementite grain diameter of not more than 1.2 μm (the fifth point in accordance with scale 2, GOST 8233-56) is preferable. The decrease in the strength properties is associated with the growth of grains and the formation of the Widmanstätten pattern (a coarse-plate mixture of ferrite with cementite) inside former austenite grains. For the HAZ material in samples with a bevel cut, the absence of the Widmanstätten pattern and the presence of latent lamellar perlite with the minimum values of the interlamellar spacing of 0.3 μm (the second point in accordance with scale 1, GOST 8233-56) are typical. In samples with a perpendicular cut, the thin-plate perlite structure (the third point) is observed, which is known [8, 10] to guarantee the combination high strength properties with high impact strength characteristics.

The data on the hardness of the cut surface of samples are shown in Fig. 7. In can be seen that the hardness of the cut surface is mainly differs only insignificantly from the hardness of the base material. A small deviation from the requirements of STO Gazprom 2-2.4-083 ($HV \leq 300$ for HAZ) is observed only in the surface zone at depths less than 100–150 μm, which helps to avoid the additional operations of its mechanical elimination during the subsequent use of groove welds made by cutting. One can also note the natural difference in the hardness distribution of the opposite edges of bevel cuts caused by the small difference in the temperature distribution over their surface in the process of cutting.

Table 3. Results of the surface study

Sample no.	Average surface roughness R_a, μm	Maximum profile height R_t, μm
501	7.60	40.73
502	2.97	20.05
503	3.60	24.57
504	3.13	20.93

Table 4. Description of the structure of samples

Sample no.	Zone	Structural data
501	HAZ_1	Latent lamellar perlite, 2nd point, interlamellar spacing of 0.30 μm
	HAZ_2	Perlite–ferrite structure, the ratio P/F = 75/25
	Base	Perlite–ferrite structure, the ratio P/F = 20/80
502	HAZ_1	Latent lamellar perlite, 2nd point, interlamellar spacing of 0.30 μm
	HAZ_2	Perlite–ferrite structure, the ratio P/F = 65/35
	Base	Perlite–ferrite structure, the ratio P/F = 5/95
503	HAZ_1	Thin-plate perlite, 3rd point, interlamellar spacing of, 0.40 μm
	HAZ_2	Perlite–ferrite structure, the ratio P/F = 85/15
	Base	Perlite–ferrite structure, the ratio P/F = 5/95
504	HAZ_1	Thin-plate perlite, 3rd point, interlamellar spacing of, 0.40 μm
	HAZ_2	Perlite–ferrite structure, the ratio P/F = 85/15
	Base	Perlite–ferrite structure, the ratio P/F = 20/80

CONCLUSIONS

(1) The quality of groove welds made using the new PMVR-5.3 narrow jet plasma torch corresponds to class 1 in accordance with the GOST 14792-80, which is higher than that provided by most of the Russian plasma torches and comparable to the cutting quality of foreign plasma torches of the same type and by laser cutting of metal of similar thickness.

(2) The microstructural analysis of the surface of groove welds made by plasma cutting using a PMVR-5.3 plasma torch indicates the possibility of performing welds with high strength properties and shows the absence of the necessity of eliminating HAZ during the subsequent manufacture of welded structures. The results of the change in the hardness of the cut surface indicate the same.

(3) The advantage of the narrow jet plasma technique is significantly higher productivity, energy efficiency, and safety of the process, which is achieved owing to the improvement of the heat input efficiency and the plasma arc stabilization.

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