Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2024 vol. 26 no. 3 pp. 149–162
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2024-26.3-149-162

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Patterns of reverse-polarity plasma torches wear during cutting of thick rolled sheets

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ARTICLE INFO

Article history:
Received: 16 June 2024
Revised: 22 June 2024
Accepted: 04 July 2024
Available online: 15 September 2024

Keywords:
Plasma cutting
Macrostructure
Wear
Nozzle
Electrode
Heat affected zone
Metal melting
Cutting parameters

Funding
The results were obtained in the framework of the Integrated Project "Establishment of production of high-tech equipment for adaptive high-precision plasma heavy cutting of non-ferrous metals for the metallurgical, aerospace and transport industries of the Russian Federation" (Agreement No. 075-11-2022-012 dated April 06, 2022) implemented by the ISPMS SB RAS at the financial support of the Ministry of Education and Science of the Russian Federation as part of Decree of the Government of the Russian Federation No. 218 dated April 09, 2010.

Acknowledgements
Research was partially conducted at core facility "Structure, mechanical and physical properties of materials" and center "Nanotech" ISPMS RAS.

ABSTRACT

The introduction describes the features of the process of plasma cutting of various metals and alloys using reverse-polarity plasma torches with and the features of cutting thick sheets. **The purpose of the work** is to study the wear process of plasma torches operating on reverse polarity current when cutting thick rolled sheets of aluminum and titanium alloys. **Research methods** include optical and scanning electron microscopy, filming of the cutting process and visual inspection of plasma torch elements after receiving specimens. **Results and discussion.** The section shows the appearance of the main working elements of the plasma torch after cutting in various modes, which led to both stable and gradual wear and to catastrophic failure of the plasma torch. The results of structural studies of the main characteristic zones of nozzles and electrodes after cutting are presented. The studies carried out made it possible to establish the main reasons for the failure of the working elements reverse-polarity plasma torches. The causes of catastrophic failure of plasma torches include failure to maintain the gap between the nozzle and the electrode and melting of the channel of gas supply into the discharge chamber. The wear of nozzles and electrodes in a stable mode can be intensified due to abnormal operation of the starting arc, the presence of manufacturing inaccuracies and excess gas pressure. **In conclusion**, the main conclusions based on the results of the research are formulated. The process of wear of electrodes, nozzles and body elements of plasma torches during operation at high electric arc power values is described.

For citation: Sidorov E.A., Grinenko A.V., Chumaevsky A.V., Panfilov A.O., Knyazhev E.O., Nikolaeva A.V., Cheremnov A.M., Rubtsov V.E., Utyaganova V.R., Osipovich K.S., Kolubaev E.A. Patterns of reverse-polarity plasma torches wear during cutting of thick rolled sheets. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2024, vol. 26, no. 3, pp. 149–162. DOI: 10.17212/1994-6309-2024-26.3-149-162. (In Russian).

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Introduction

Plasma cutting of various metals and alloys has advantages for industrial applications related to high productivity, cutting quality and the ability to cut hot-rolled plates [1–3]. The plasma cutting is an effective method for obtaining workpieces from steels [4], aluminum [5], copper [6], titanium [7] alloys. When cutting, it is possible both to form a clear cut at an angle of 90 degrees to the surface of the sheet, and to form the necessary cutting edges for further welding of structures [8]. Mainly, equipment operating on direct polarity current [9, 10], which has limitations for cutting hot-rolled plates, is used for plasma cutting.

The use of plasma cutting technology with reverse polarity current makes it possible to increase the productivity of the process [11–14], especially in the production of large capacity workpieces. Actually in the literature there is quite a small amount of data on cutting of non-ferrous metal and alloy sheets with a thickness of about 30–100 mm [15–18]. At the same time, plasma cutting of thick plates has difficulties associated with high values of plasma arc current and its intensive impact on the working elements of the plasma torch. In addition to studies aimed at establishing the influence of cutting process parameters on the surface quality and structural-phase changes in the impact of the plasma jet on the material [12, 16], it is necessary to carry out work in the field of changing the state of the plasma torch during cutting. This is especially relevant from the point of view of economic efficiency of plasma cutting with reverse polarity current, since it is characterized by a lower degree of wear of plasma torch elements during operation [11].

Plasma cutting with reverse polarity current, despite the long operating time, is a promising method for obtaining workpieces from thick plates in industry. Plasma cutting with reverse polarity current is the most relevant for obtaining workpieces from thick sheet metal. This is due to the lower current values at the same thickness of the cut plates in comparison with cutting with direct polarity current. The systems with a hollow anode used for cutting with reverse polarity current allow obtaining lower current density on its surface in comparison with thermochemical cathodes for cutting with direct polarity current, which also contributes to the increase of plasma torch life. For these reasons, plasma cutting with reverse polarity current for thick plates is more relevant both in terms of process efficiency and from the point of view of equipment reliability and durability. In this direction, the development of modern design solutions and the development of domestic plasma cutting equipment with a number of advantages in comparison with existing analogues are currently required. At present time, within the framework of the joint project of ISPMS SB RAS and "ITS-Siberia" modern equipment for plasma cutting of thick rolled non-ferrous metals and alloys of large thicknesses with a reverse polarity current is being developed. The purpose of this work is to identify the main regularities of the process of failure of working elements of plasma torches of the developed design depending on various factors in the cutting process.

Materials and methods

The studies were carried out at the manufacturing area of "ITS–Siberia" and on experimental equipment at ISPMS SB RAS. Cutting was carried out on a plasma torch with reverse polarity, developed in the course of a joint scientific and technical project. The scheme of the plasma cutting process is shown in Figure 1, *a*. The plates **1** were cut by a plasma jet **2** formed in the environment of a protective and plasma-forming gas **3** due to the burning of the starting arc **4** at the start of the process and the working arc **5** during cutting. The supply of protective and plasma-forming gas **6** to the cutting zone is performed at fixed pressure from the compressor. Nozzle **7** is fixed by a nut **8** and serves to form a dense jet of gas and plasma **9** formed by swirl ring **10** and arcing. Additionally, the plasma torch of the developed design provides for the introduction of water **11** into the cutting zone through the hole in the working electrode **14**. This allows increasing the quality of the cut and reducing the wear of the nozzle and electrode [19, 20]. Protection against overheating of the nozzle and electrode is also provided by a constant flow of water **12** through channels in the body **13**. Water supply in the plasma torch is arranged in such a way that the flow **13** first washes the nozzle, then the electrode, and then is carried partially to the exit of the plasma torch and into the inner cavity of the nozzle and then by the flow **11** into the working zone. Current is supplied to the electrode through a copper

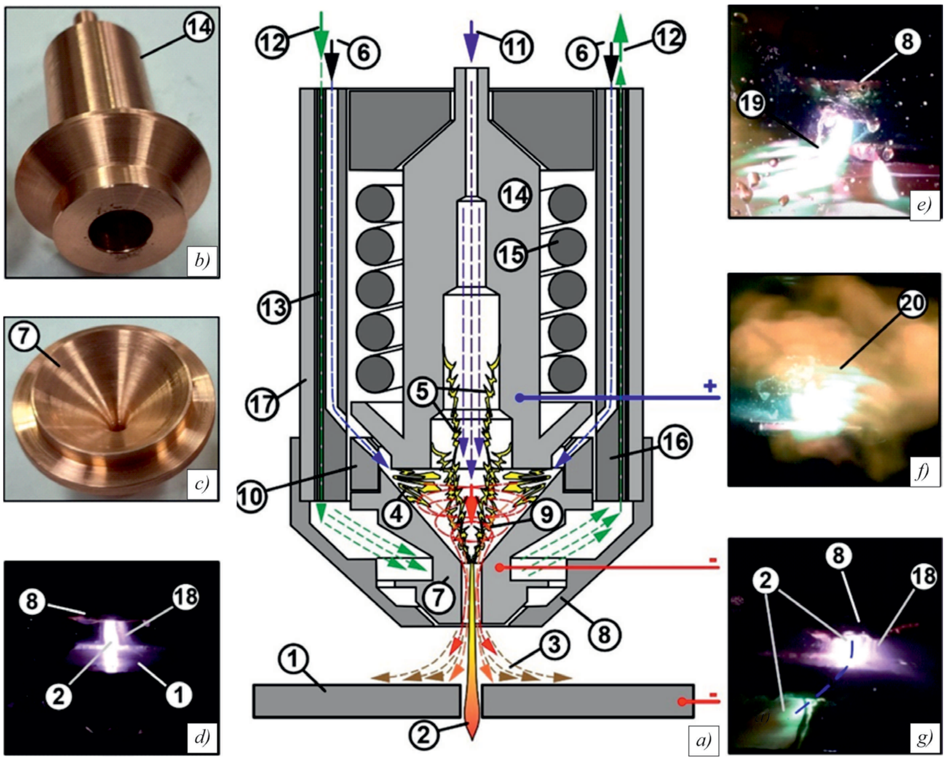

Fig. 1. The operational scheme of the reverse-polarity plasma torch (*a*), the appearance of the working electrode (*b*) and nozzle (*c*), the cutting process under normal conditions (*d*), the start of the cutting process (*e*), the process of external arc burning (*f*) and cutting with excess speed (*g*):

1 – plate; 2 – plasma jet; 3 – gas flow; 4 – starting arc; 5 – working arc; 6 – flow of plasma-forming and protective gas; 7 – nozzle; 8 – external nut; 9 – vortex flows of gas and plasma; 10 – swirl ring; 11 – water supply to the hollow electrode; 12 – supply of cooling water to the plasma torch body; 13 – water cooling channels; 14 – electrode; 15 – solenoid; 16 – inner casing made of fluoroplastic; 17 – outer steel casing; 18 – "water mist"; 19 – arc burning at the moment of starting; 20 – external arc burning

solenoid **15**, additionally forming a magnetic field to focus the plasma flow and electric arc. The inner body of the plasma torch **16** with water and air supply channels is made of fluoroplastic, and the outer body **17** is made of steel. The working electrode **14** (Figure 1, *b*) and nozzle **7** (Figure 1, *c*) are made of *M1* copper.

Operation of the plasma torch in the standard mode is associated with the formation of a plasma jet around the plasma-forming arc (Figure 1, *d*). Water supply to the cutting zone leads to the formation of "water mist" **18** (Figure 1, *d*). The presence of water mist during cutting accelerates the process of material cooling and makes it possible to cut aluminum alloys without a protective atmosphere in the form of nitrogen, since the oxidation of the edge is minimal and the quality of the cut is high enough [19, 20].

The main difficulties in cutting arose at the start of the process, when the starting arc is ignited and then the working arc **19** with the plasma column is formed (Figure 1, *e*). In this case, if the process is normal, the plasma column is formed, the arc is short-circuited between the sheet and the electrode, and the plasma jet is turned off (Figure 1, *d*). If there are problems at the start, the effect of external arcing can be realized (Figure 1, *f*), when the ignition of the working arc does not support the formation of a plasma jet.

Cutting was carried out according to the modes typical for aluminum and titanium alloy plates 60–100 mm thick. The development and optimization of cutting modes for hot-rolled non-ferrous metal plates was carried out earlier in [13–16]. The current of the electric arc ranged from 300 to 370 A, the voltage from 300 to 400 V, the height of the plasma torch above the surface of the plate during the cutting process was from 16 to 25 mm. The gas pressure was from 2.0 to 4.0 bar, the water pressure in the system before entering the plasma torch cooling circuit was 6 bar, the gap between the nozzle and the electrode was from 0.5 to 2.0 mm. Cutting speed was from 250 to 3,000 mm/min. Air was used as a plasma-forming gas. The main purpose of the work was to describe the characteristic wear patterns of nozzles and electrodes of the plasma torch during operation and to identify the causes of its occurrence.

After obtaining experimental samples of worn-out plasma torch nozzles and electrodes, specimens for structural studies were cut out of it using the electrical discharge machining (*DK7750* machine). Structural studies were carried out on an optical microscope *Altami MET 1C*, laser scanning microscope *Olympus LEXT 4100* and scanning electron microscope *Zeiss LEO EVO 50*.

Results and discussion

Plasma cutting of hot-rolled products at currents of more than 300 A results in significant damage to consumables (Figure 2). The most significant damage occurs during the starting of process during operation of the starting arc, after that the main mechanism of nozzle and electrode wear is erosion during interaction with the gas-plasma flow.

At the initial stage of the process, the accuracy of the interface between the nozzle and the electrode is of particular importance, the gap in which for a plasma torch of this design should be about 1.0–1.5 mm.

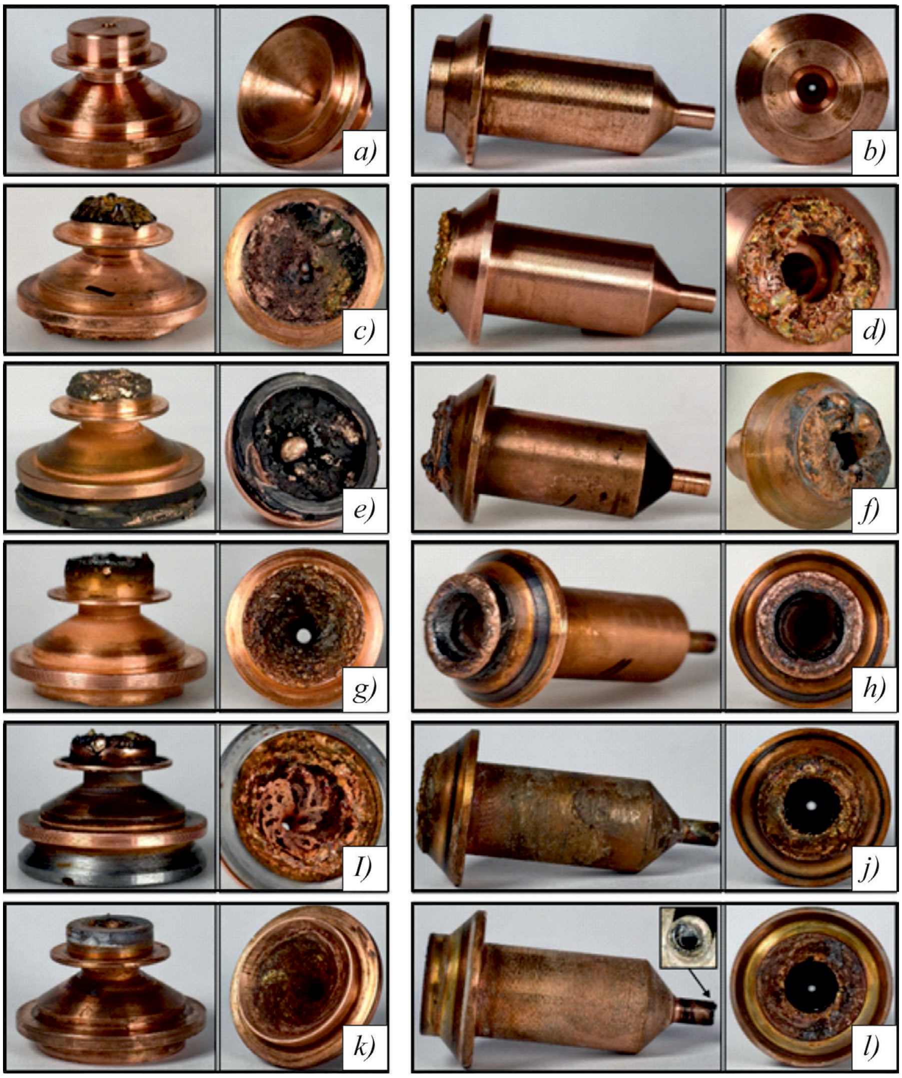

Fig. 2. The appearance of nozzles (*a*, *c*, *e*, *g*, *i*, *k*) and electrodes (*b*, *d*, *f*, *h*, *j*, *l*) before testing (*a*, *b*), when tested in the condition of non-observance of the gap between the nozzle and electrode (*c*, *d*), when testing with melting of the gas supply holes in the swirl ring (*e*, *f*), when testing without turning off the starting arc (*g*, *h*) and with insufficiently precise manufacturing of the nozzle (*i*, *j*) under conditions of low gas pressure, and when tested in optimal cutting conditions without defects (*k*, *l*)

With a small gap, the risk of prolonged double arcing during the operation stage or short circuit to the discharge chamber when arcing increases, which can lead to catastrophic failure of the working elements (Figure 2, *c*, *d*).

One of the reasons for the plasma torch failure can be the melting of holes in the swirl ring, leading to a sharp increase in temperature in the cavity between the electrode and the nozzle due to the lack of heat removal by the gas flow (Figure 2, *e*, *f*). As a result, the metal of the nozzle and electrode melts sharply and the nozzle hole is blocked.

The process of gradual wear of the nozzle and electrode material is mainly associated with high-temperature erosion during the interaction of copper with the plasma and gas flow (Figure 2, *g*–*l*). This process can be further complicated by the operation of the starting arc during cutting (Figure 2, *g*, *h*) or by inaccuracy in the manufacture of plasma torch elements (Figure 2, *i*, *k*).

With an average operating time per failure of more than 250–300 starts of consumable elements (nozzle and electrode) in the process of cutting hot-rolled plate (up to 100 mm) products, untimely starting arcing off or inaccuracies in manufacturing can reduce this parameter to 100–150 starts. The processes of catastrophic failure of plasma torch lead to its abrupt failure even after one start. The reason is mainly insufficient clearance between nozzle and electrode. The temperature in the zone of the discharge chamber rises so high in a short time that the metal begins to melt and boil, leaving a characteristic structure on the surface in the form of a melting zone with a large number of pores (**2** in Figure 3). Moreover, there are practically no traces of oxides or erosion products on the electrode surface, and the thin melting zone **2** passes into the base metal **1** (Figure 3, *a*, *c*–*e*). The inner surface of the nozzle has traces of oxidation, metal boiling and erosion (Figure 3, *b*, *f*–*h*). The metal entering the nozzle channel quickly crystallizes and plugs it. The

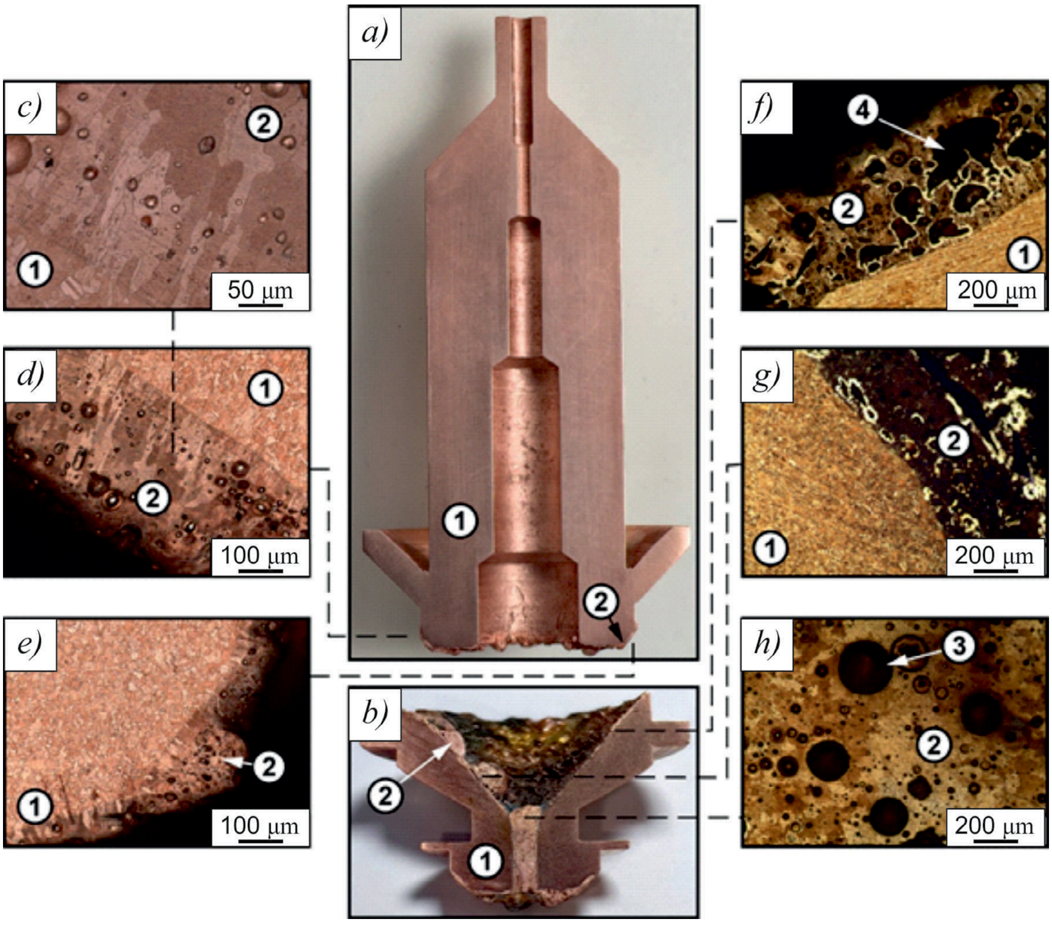

Fig. 3. The structure of plasma torch elements after a catastrophic failure of the nozzle and electrode with insufficient clearance between it:

a, *b* – macrostructure of the electrode and nozzle, *c*–*e* – microstructure of individual sections of the electrode; *f*–*h* – microstructure of nozzle sections pores in the melted material are mainly spherical **3** or irregularly shaped **4** (Figure 3). On the plasma torch of the developed design, gas pressure less than 2 bar increased the risk of formation of this phenomenon. Increasing the pressure above 2.5-3.0 bar and setting the gap between the nozzle and the electrode not less than 1.0-1.5 mm practically canceled the risk of failure of the plasma torch as a result of double arc formation or short circuit in the discharge chamber.

The second type of catastrophic failure of plasma torches of this design is melting of channels in the swirl ring (Figure 4). In this case, during operation, due to the fairly close location of the junction of the swirl ring and nozzle to the discharge zone (Figure 4, *b*), its partial fusion may occur. During operation, the distortion of the elements in this area gradually accumulates under the action of the starting arc to such an extent that the gas supply holes are partially blocked, which causes the temperature of the nozzle and electrode to rise sharply. Then, as in the previous case, it suddenly melts, boils and plugs the nozzle hole. At the same time, on the surface of both the electrode and the nozzle there are signs of erosion and oxidation during operation.

This phenomenon occurs partly for design reasons, and partly due to insufficient clearance between the electrode and the nozzle during assembly. It is possible to reduce the risk of this process by adjusting this clearance at a level of 1.0–1.5 mm.

During plasma cutting, ignition of the starting arc between the electrode and the nozzle forms the initial plasma flow into the cutting zone, after which it is switched to the working arc and cutting in the normal mode. If the starting arc is not switched off in time during operation, it is possible to increase the intensity of wear of working elements of the plasma torch and formation of deposits on the electrode surface (Figure 5). According to the data of scanning electron microscopy, the composition of deposits (**5**, **6** in Figure 5)

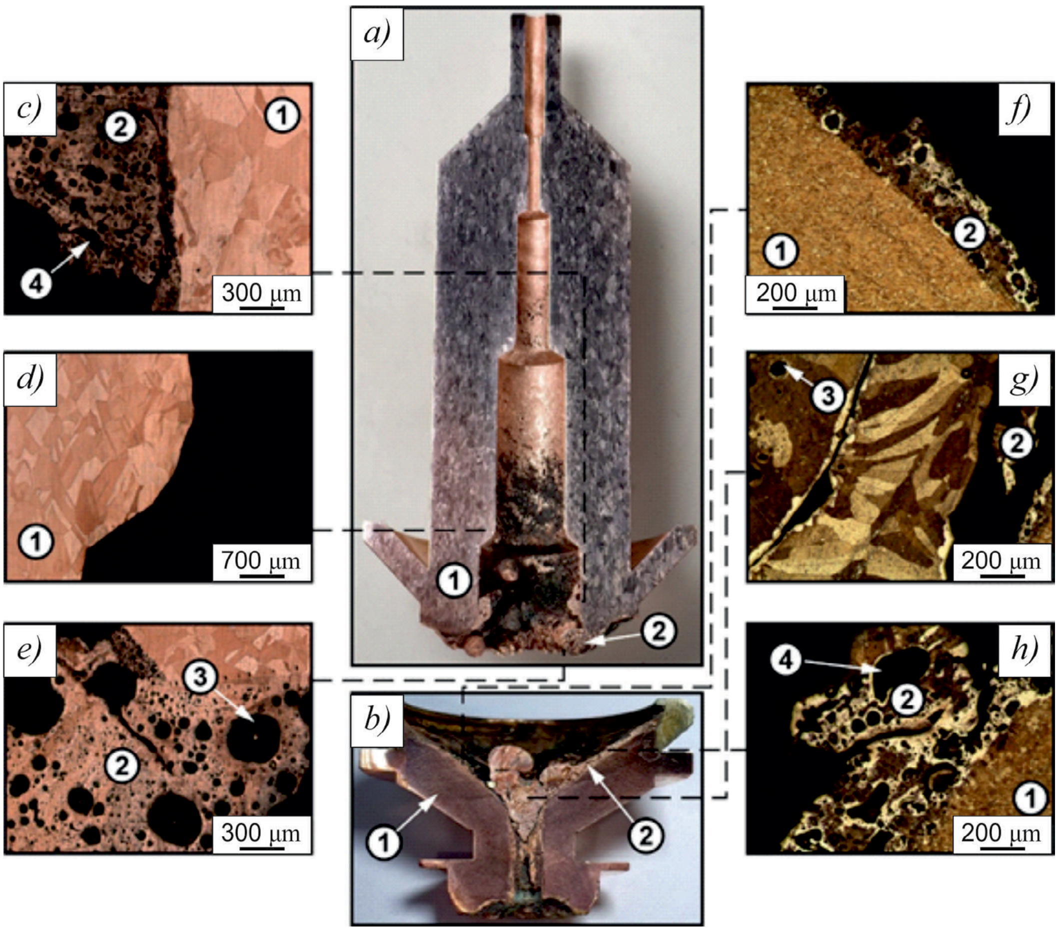

Fig. 4. The structure of plasma torch elements after a catastrophic failure of the nozzle and electrode due to clogging of the gas supply channels in the swirl ring:

a, *b* – macrostructure of the electrode and nozzle, *c*–*e* – microstructure of individual sections of the electrode; *f*–*h* – microstructure of nozzle sections

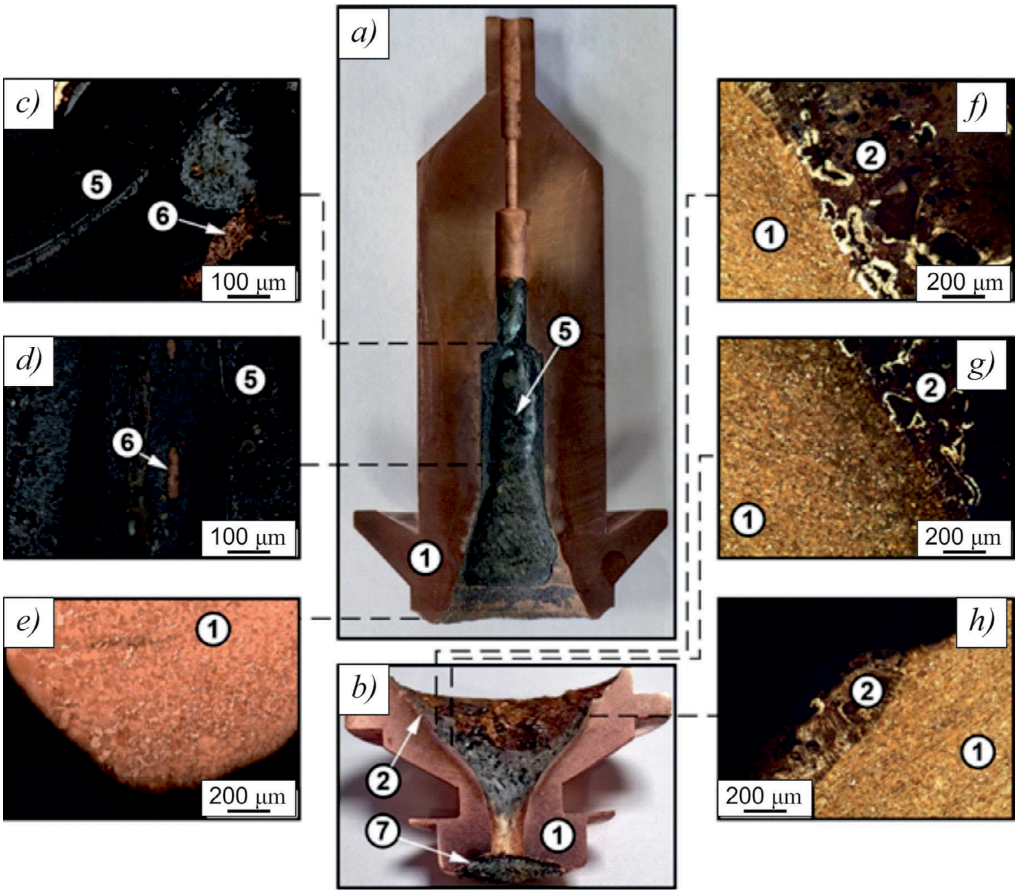

Fig. 5. The structure of the plasma torch elements after the gradual failure of the nozzle and electrode during constant operation of the starting arc:
a, *b* – macrostructure of the electrode and nozzle; *c*–*e* – microstructure of individual sections of the electrode; *f*–*h* – microstructure of nozzle sections

includes impurities that were part of the water, copper and oxygen. There is also a significant amount of oxygen on the nozzle surface. Nozzle and electrode wear accelerates in comparison with wear in normal mode, but in this case, the consumables withstood up to 150 starts when cutting hot-rolled products.

Separately, we can emphasize the influence of nozzle and electrode manufacturing accuracy on the wear of working elements. When operating in normal mode without a significant excess of wear intensity of the working elements of the plasma torch, deviation from the nominal position of the nozzle hole causes its uneven wear (Figure 6). In the case presented in Figure 6, when manufacturing the nozzle, the misalignment of the nozzle outlet and conical nozzle cavity of the order of 0.4-0.5 mm was allowed. This caused the initial deviation of the arc and plasma column during cutting from the vertical orientation and more significant wear at an angle to the vertical axis, which with the time of operation increased and led to even more significant changes in the shape of the nozzle. The irregularity of electrode wear is also evident. Timely starting arcing off, control and observance of the gap between the nozzle and electrode, gas pressure in the system and water supply lead to a small risk of catastrophic wear of consumables and formation of deposits on the electrode surface. However, uneven wear leads to deviation of the plasma jet from its nominal position and, as a consequence, to insufficient cut quality after 100–150 starts. For this reason, the alignment of the hole at the outlet and in the conical part in the nozzle of the plasma torch should be at a high enough level to ensure the accuracy of the cut during operation of the plasma torch.

Cutting of specimens in the standard mode is characterized by the minimum intensity of wear of consumable elements, which is shown in Figure 2, *l*, *k*. Increasing the gas (air) pressure in the system from 2.0–2.5 to 3.0–3.5 bar increases the service life of consumable elements of the plasma torch by more than two times and reduces the risk of double arcing during operation. Increasing the pressure in the discharge

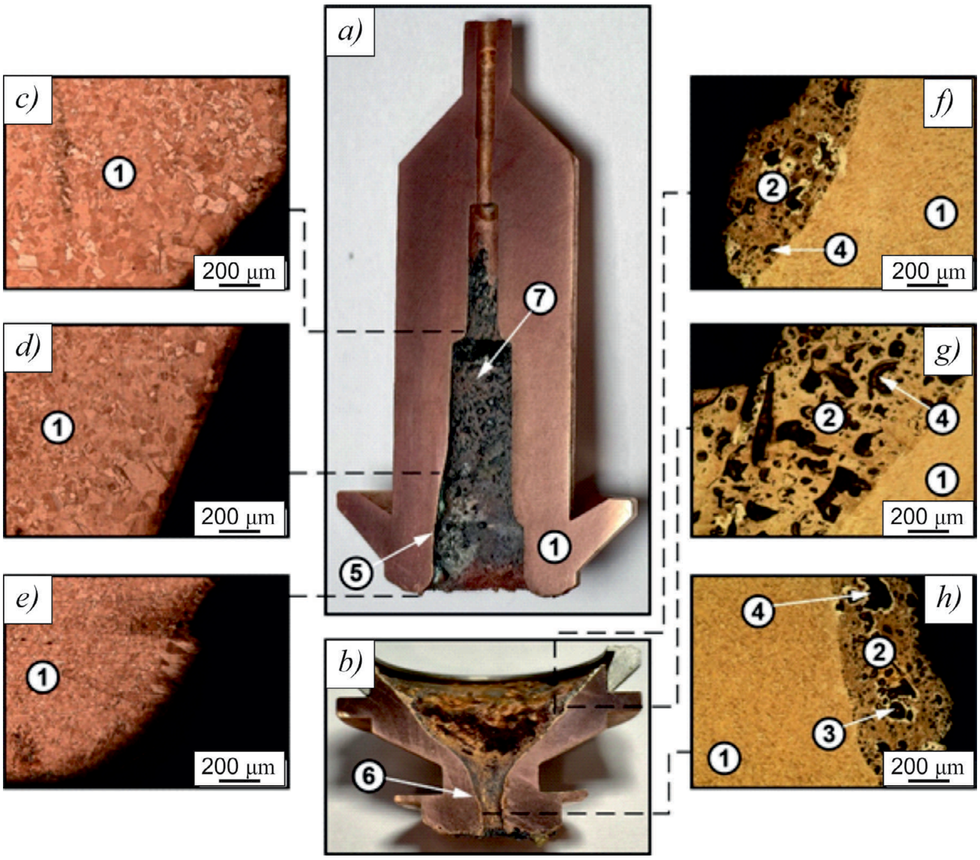

Fig. 6. The structure of plasma torch elements after gradual uneven wear of the nozzle and electrode under conditions of inaccuracy in the manufacture of consumable elements:

a, *b* – macrostructure of the electrode and nozzle, *c*–*e* – microstructure of individual sections of the electrode; *f*–*h* – microstructure of nozzle sections

chamber, if the water pressure at the plasma torch inlet is not observed, leads to partial squeezing of gas and plasma into the electrode hole and its erosion, which can be observed during visual inspection (Figure 2, *l*, *m*). Increasing the resistance to water flow at the outlet of the plasma torch also made it possible to level out this defect in operation, even in the presence of inaccuracies in the manufacture of the nozzle or untimely starting arcing off, which can be seen from the absence of damage in the upper part of the working electrodes in Figures 5 and 6.

Conclusion

The process of plasma cutting with reverse polarity current is quite complex and non-uniform in time and on a large number of different factors. The conducted studies show that, similarly to a number of previously conducted studies on direct polarity plasma torches and on smaller thicknesses of cut sheet metal [11, 16, 20 and others] the main of the most dangerous factors for fatal failure of working elements of plasma torches under conditions of cutting thick sheet metal of titanium and aluminum alloys with the reverse polarity current are failure to maintain the gap in the discharge chamber and low gas pressure in the system. This can cause double arcing during cutting and short circuit between electrode and nozzle through the molten metal. Maintaining the minimum gap and gas pressure above 2.5–3.0 atmospheres can significantly reduce the risk of fatal failure of nozzles and electrodes. The use of water injection technology into the working zone allows improving the quality of the cut and the duration of operation of the consumables, which is also described in [17, 18], but can lead to some increase in electrode wear due to insufficient resistance to the water flow at the outlet of the plasma torch. Misalignment of the conical part of the nozzle and the hole at its outlet leads to a faster failure of both the nozzle itself and the working electrode due to uneven wear. In addition, increased wear of the working elements of the plasma torch can ensure untimely starting arcing off when switching to the operating mode. In normal operation, the wear of the working elements of the plasma torch developed during the implementation of the joint project of ITS Siberia and ISPMS SB RAS when cutting aluminum and titanium alloy sheets up to 100 mm thick with a reverse polarity current, although quite intense in comparison with cutting sheet metal of smaller thicknesses, currently allows for more than 250–300 starts with different cutting lengths.

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Conflicts of Interest

The authors declare no conflict of interest.