Antoni Sawicki

Selected Properties of High-Frequency Electric Arc Initiators and Stabilisation Oscillators.
Part 2. Devices with Compressed Electric Arc

Abstract: The second part of the overview article discusses general features of the design and operation of selected industrial arc plasma torches. Because of their structural and operating differences, plasma torch power supply systems with internal and partly external arc are discussed separately. Particular attention was paid to the design of electric systems used for the initiation of arc discharges. Because of the fact that the operation of plasma torches with partly external arc is often accompanied by the formation of double arc, the article also presents measures and methods enabling the prevention of the aforesaid unfavourable phenomenon. In addition, the article discusses selected technological properties of plasma torches and micro-plasma torches used for joining, cutting, surfacing and hardening.

Keywords: electric spark, electro arc, welding ioniser, plasma torch

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Introduction

In spite of the fact the goals and methods of operation of ignition systems in devices with free and compressed arc are nearly the same, various structural features of torches may give rise to different designs and trigger different functioning of electric discharge initiating systems. Torches used in TIG welding processes are usually equipped with a ceramic nozzle (not playing a role in arc initiation). Ignition is usually affected, among other things, by the initial distance between the tungsten electrode and a semi-finished product subjected to welding. As a result, particularly in terms of manual welding, ignition may be delayed or a short circuit may occur because of an inaccurately positioned welding torch.

In relation to plasma torches with partly external arc, a distance between the electrode and a semi-finished product is relatively long. In addition, the beginning and the initial stage of the welding process are accompanied by the relatively intensive flow of cold gas, impeding the obtainment of the significant concentration of ions and the ignition of arc. For this reason, ignition takes place inside the torch - between the electrode and a nearby metal nozzle, incorporated in the circuit with the ioniser system. Only after the initial development of arc ignition, it can be transferred by the increased flow of gas through the narrow nozzle gap to a semi-finished product connected to the welding power source. As a result, the process of ignition is not delayed and the welder can more

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easily observe a semi-finished product area illuminated by arc.

Presently, plasma torches, enjoying growing popularity in various industries, are used in joining, cutting, surfacing or hardening processes, involving the use of various values of current and, consequently, various values of arc power. Particularly useful are low-power devices for micro-welding, micro-cutting, micro-surfacing etc.

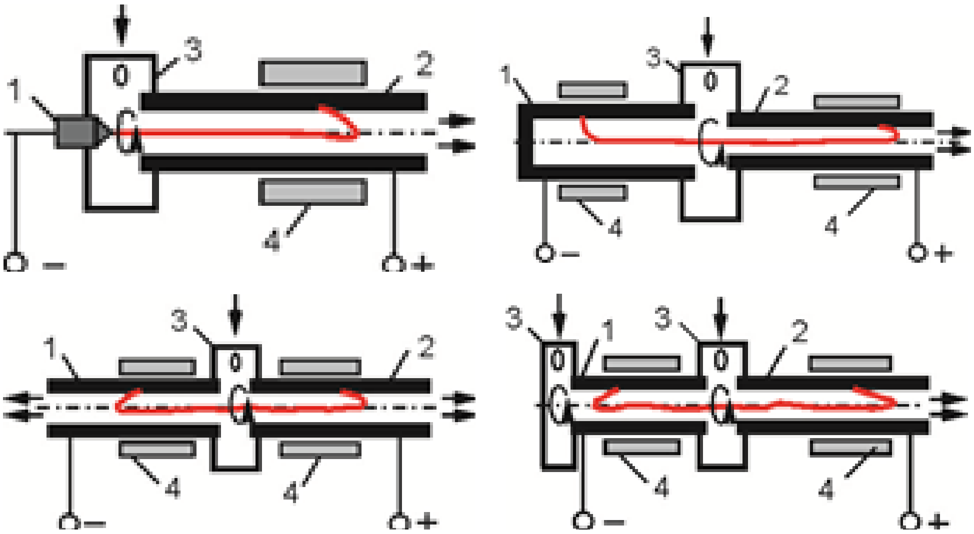


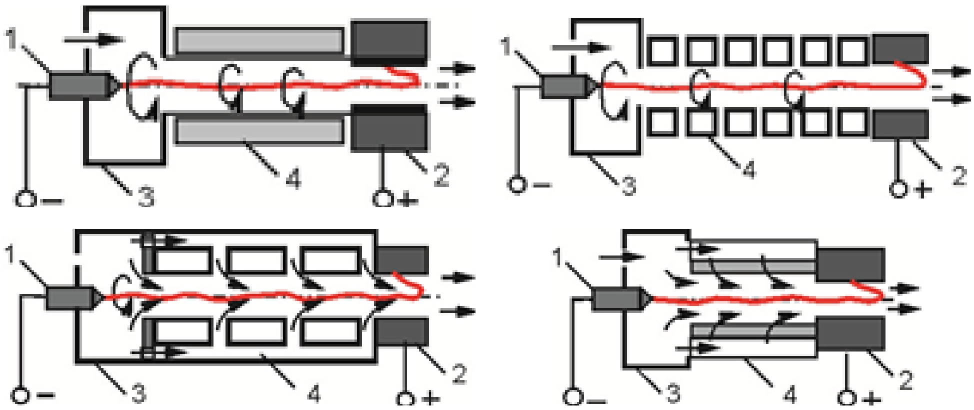
Fig. 1. Schematic diagrams of DC plasma torches with a self-adjusting arc column length: a) DC plasma torch with the internal pin cathode, b) DC plasma torch with the internal tubular electrode, c) DC plasma torch with two-sided gas flow and d) two-chamber DC plasma torch with auxiliary rotational gas flow (1 – cathode, 2 – anode <constrictor-nozzle>, 3 – whirl chamber and 4 – solenoid) [1]

General features of selected designs of arc plasma torches

Arc plasma torches represent various categories depending on their primary features and, therefore, can be divided into the following types:

- DC and AC (one-phase or multi-phase) arc plasma torches,
- single-arc and multi-arc plasma torches,
- arc plasma torches with internal, partly external and fully external arc,
- arc plasma torches with a gas stream washing around arc longitudinally or transversely,
- arc plasma torches with a self-adjusting, fixed or periodically variable column length,
- arc plasma torches with the cold or hot cathode,
- arc plasma torches with the gaseous or liquid medium,
- arc plasma torches for continuous or pulsed operation.

Examples of simplified designs of stream plasma torches are presented in Figures 1 and 2. The plasma torches presented in the above-named Figures are used to heat gases, spray coatings, process non-conductors etc. The solenoid is tasked with triggering the movement of an arc spot, making it possible to reduce the erosion of cold electrodes.



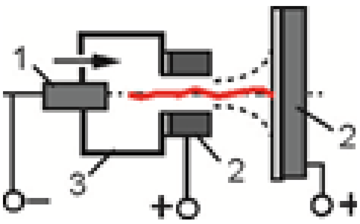


Fig. 2. Schematic diagrams of DC plasma torches with a fixed arc column length and with: a) dielectric constrictor, b) water-cooled selectable constrictor, c) water-cooled selectable constrictor with additional internal gas flow, d) dielectric porous constrictor and e) partly external arc (1 – cathode, 2 – anode, 3 – whirl chamber and 4 – chamber housing) [1]

The processing of conductors usually involves the use of plasma torches with external arc. Entirely external arc surrounded by a longitudinal gas stream is used in plasma torches for melting in plasma furnaces [2]. In turn, arc partly external in relation to the plasma torch nozzle, also washed around by the gas stream, are used, among other things, in welding engineering to process metal elements (Fig. 3).

Because of their simple design, DC plasma torches are reliable and most commonly used in technological processes. They are usually made as high-power (frequently three-phase) devices with three arcs combined into a triangle or a star [3].

There are two methods, in which materials are subjected to plasma processing.

1. The first method involves arc burning between the plasma torch and the semi-finished product. This method is applied in a direct cutter, where the semi-finished product should conduct electric current.
2. In the second method, arc is ignited inside the plasma torch between the electrode and the nozzle. The electrode is the cathode, whereas the nozzle is connected to the positive potential of the power supply. This method is applied in an indirect cutter, where the semi-finished product should not conduct electric current.

The gradual start-up of the plasma torch consists of two stages [4]:

– discharge ignition with a small stream of gas under low pressure,
– ignition is followed by increasing the flow rate and pressure of gas up to nominal values.

Plasma torches can be ignited by:

– momentary contact of the electrodes (e.g. using auxiliary electrodes),
– momentary insertion of a rod connecting the electrodes,
– current pulse-triggered explosion of a thin wire,
– stream of electrolyte,
– stream of liquid metal,
– high-frequency high voltage.

The layer of gas washing around the arc column remains relatively cold (T < 6000 K), forming thermal and electric insulation between plasma and the metal chamber or the nozzle duct. The density of current in plasma torch arc reaches 100 A/mm², whereas its temperature is restricted within the range of 15000 K to 30000 K.

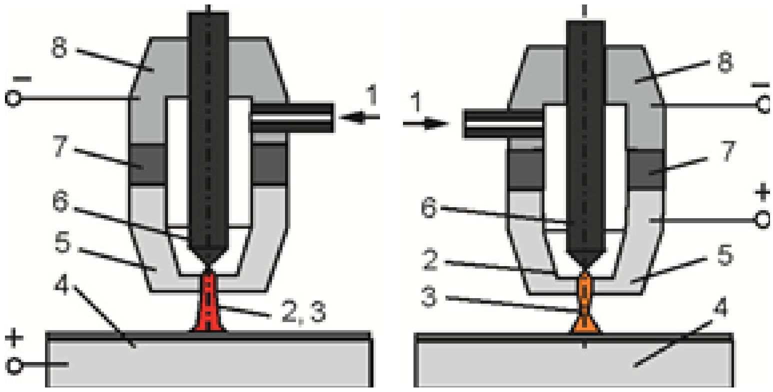


Fig. 3. Typical plasma torches used in welding engineering: a) with partly external arc and b) with internal arc (1 – gas inflow, 2 – arc, 3 – gas stream, 4 – semi-finished product, 5 – tip with the nozzle, 6 – cathode, 7 – insulator and 8 – cathode node)

Selected properties of plasma torch supply systems with internal arc

In plasma torches of indirect operation, arc is generated inside the discharge chamber, between the electrode and the nozzle. It is only an increased gas flow that blows out high-heated gas, forming a conical stream with its peak usually directed towards the surface of the semi-finished product. The cone is also surrounded by heated gas.

The start-up of a plasma torch and its reliable operation depend on the efficient operation of the arc excitation system (decisive for the wear resistance and service life of electrodes). Because of the method of developed arc discharge excitation, plasma torches feature one, two or multi-stage ignition systems. In plasma torches with a self-adjusting arc column length, the excitation of discharge requires the formation of an area which conducts in accordance with the one-stage excitation scheme.

In plasma torches, the excitation of discharge is obtained by:

– initial and direct contact of electrodes,
– contact of electrodes using a thin wire,
– pouring a small amount of electrolyte into the chamber; the electrolyte evaporates after

ignition,
- initial use of a neon-argon mixture under atmospheric pressure (a gap of between 1mm and 4 mm requires voltage restricted within the range of 200 V to 300 V),
- use of an ioniser generating high-voltage and high-frequency impulses,
- use of an additional (auxiliary) plasma torch.

If inter-electrode gaps are large, it is necessary to use moving electrodes or to provide gas with easily ionising admixtures. An additional (auxiliary) plasma torch also requires the use of an ignition system, yet of significantly lower power and voltage.

Figure 4 presents two power supply systems of plasma torches with a self-adjusting arc column length. Figure 5a presents an ioniser (2) connected in series (in the circuit) with the cathode (3). The welding power source is protected against high-voltage impulses by a choking coil (L) and capacitors (C1 and C2). In turn, Figure 5b presents an ioniser (2) connected in series (in the circuit) with the cathode (3) and the constrictor-nozzle (4). The flow of current from the welding power source (1) triggers the operation of a relay (5) and the shut-down of the oscillator (2). The results of the operation of the above-named systems are nearly the same as those discussed in publication [5]. The ioniser connected in series should be adjusted to the nominal current of the plasma torch. An advantage of such a solution is the low effect of generated interference on the operation of the power source (1). In turn, if the ioniser is connected in parallel, it does not have to conduct nominal current and can be adjusted to any plasma torch having a permissible initial width of the inter-electrode gap. A disadvantage of such a solution is the high level of interference affecting the welding power source and the supply network.

Plasma torches with the sectional constrictor require the consecutive switching of the ioniser, starting from the electrode located near the cathode up to the electrode-nozzle (leading to the gradual extension of the arc column). The schematic diagram of such a system is presented in Figure 5. The control unit (4) switches on (consecutively) the next contactor (C-K), almost simultaneously switching off the previous one. The ioniser system is switched off after arc has reached the nozzle.

Publication [7] presents systems enabling the combined ignition of primary arc using spark discharge and auxiliary arc. Specific solutions are presented in Figure 6, showing ionisers connected in parallel to the welding power source. In Figure 6a, the shorting of the switch (K) is followed by the initiation of arc between the cathode (3) and the auxiliary electrode (4). The opening of the switch (K) is accompanied by the jump

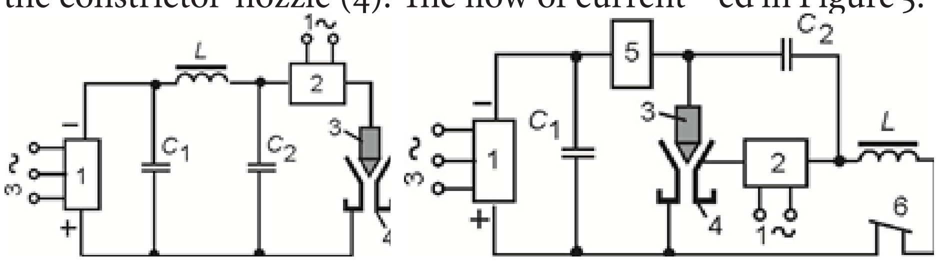


Fig. 4. Schematic diagrams of systems used to excite electric arc in plasma torches: a) serial and b) parallel (1 – welding power source, 2 – ioniser, 3 – cathode, 4 – constrictor-nozzle, 5 – contactor and 6 – contact) [6]

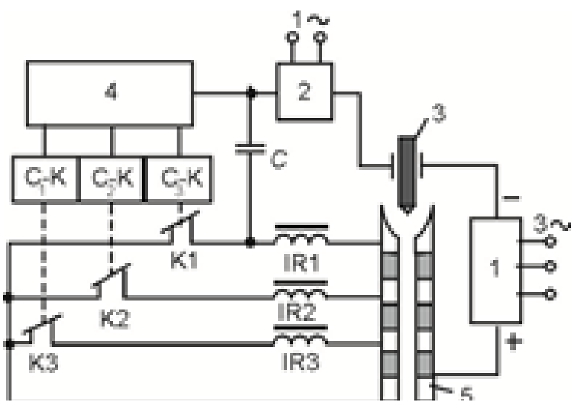


Fig. 5. Schematic diagram of the parallel system for the excitation of electric arc in the plasma torch with the sectional constrictor (1 – welding power source, 2 – ioniser, 3 – cathode, 4 – control unit, 5 – constrictor sections and nozzle, C-K – contactors and K – contacts) [6]

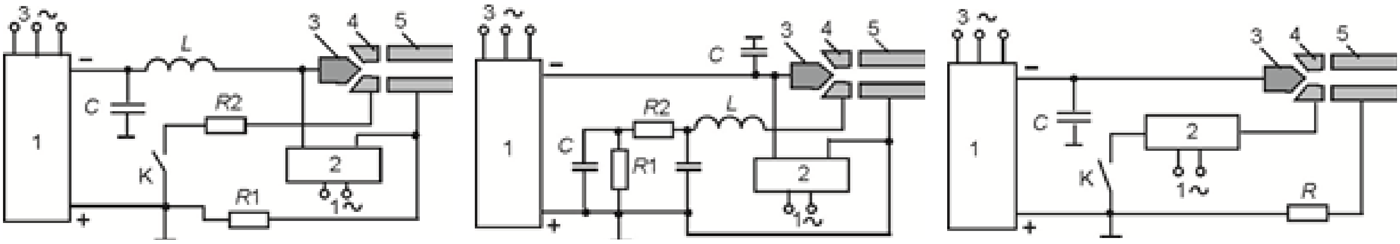


Fig. 6. Schematic diagrams presenting the start-up of the sectional plasma torch with auxiliary arc and spark ignition: a) with the ioniser connected in parallel and the switch, b) with the ioniser connected in parallel and the passive system, c) with the ioniser connected in the circuit with the auxiliary electrode (1 – welding power source, 2 – ioniser, 3 – cathode, 4 – auxiliary electrode and 5 – electrode-nozzle) [7]

of the arc anode spot from the electrode (4) onto the nozzle (5). In Figure 6b, the role of the switch is played by a system composed of appropriately selected passive elements (RLC). In Figure 6c, the operation of the oscillator in two parallel circuits corresponds to the short-circuited switch (K). One of the circuits contains the cathode (3), whereas the other one contains the anode-nozzle (5). The initiation of discharge between the cathode (3) and the nearby auxiliary electrode (4) is followed by the shut-down of the switch (K) and the jump of the anode spot from the electrode (4) onto the nozzle (5).

Selected features of the design and power supply of plasma torches with partly external arc

In plasma torches of direct operation, plasma arc burns between the electrode fixed inside the chamber and the semi-finished product located outside. During normal operation, the nozzle (in spite of being made of metal) usually remains neutral in relation to the cathode node and is used to compress and stabilise arc. Arc is cylindrical and slightly widens near the semi-finished product surface. Because of the compression of the arc column in the nozzle area and more intense washing around by the flow of gas, the temperature of plasma and its enthalpy are higher than those in plasma torches with internal arc.

Because of a relatively long distance between the electrode and the semi-finished product, the direct excitation of arc is difficult. For this reason, it is necessary to initially excite auxiliary arc between the electrode and the nozzle. Once the flame of hot gas has affected the semi-finished product, primary arc is ignited automatically between the electrode and the semi-finished product. At the same time, the arc spot on the nozzle surface should disappear.

The methods of auxiliary arc ignition are the following:

- short short-circuiting of the cathode-nozzle section using a movable conducting insert,
- excitation of spark discharge using the high-frequency high-voltage generator.

The procedure of the ignition of primary arc is the following [8]:

- auxiliary arc is initiated between the cathode and the tip of the nozzle shaping the stream of gas (current should be restricted within the range of 30 A to 50 A), preferably using gas of high enthalpy (e.g. nitrogen),
- gas mass stream is increased in order to move the auxiliary arc anode spot from the upper surface of the nozzle to its lower surface,
- flame (having a length restricted within the range of 15 mm to 25 mm) affecting the element connected with the welding power source triggers the formation of cutting arc and the disappearance of auxiliary arc,
- gradual increasing of current up to between 300 A and 500 A, with the possibility of changing the chemical composition of gas.

Figure 7 presents successive stages of discharge generation and development. Figure 8 presents corresponding gas pressure curves and arc current waveforms.

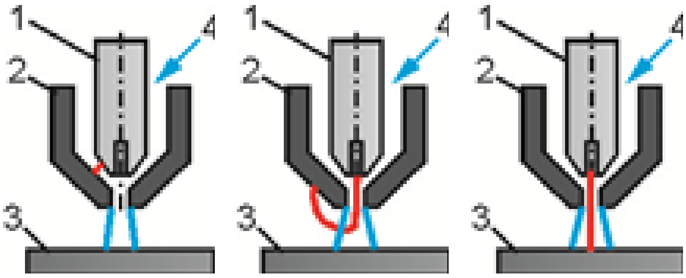


Fig. 7. Successive stages of discharge in the plasma torch: a) initial arc following the breakdown of the gas layer, b) auxiliary arc between the cathode and the metal nozzle and c) primary arc between the nozzle and the semi-finished product (1 – cathode, 2 – nozzle and 3 – semi-finished product)

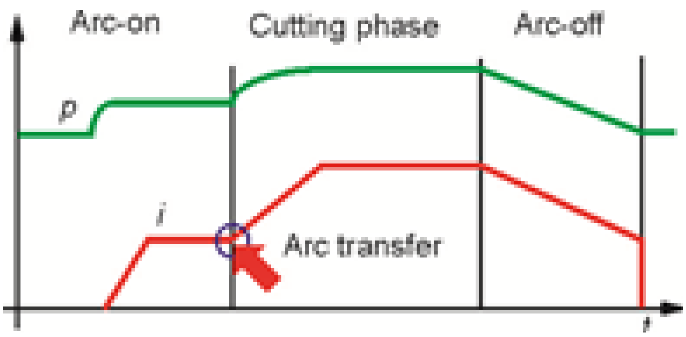


Fig. 8. Curves of gas pressure and waveforms of current in the plasma torch – at the individual stages of operation – from arc ignition to arc termination

Similar to non-consumable electrode arc welding, also in plasma arc welding the oscillator can be connected in series or in parallel. Designs of ignition systems are presented in Figure 9. In Figure 9a, the ioniser is connected in series with the cathode. In turn, in Figure 9b, the ioniser is connected in series with the nozzle. In Figure 9c, the ioniser is connected in parallel with the plasma torch. Switching on the key (K) triggers the ignition of auxiliary arc between the cathode (3) and the nozzle (4), whereas switching off the key (K) triggers the jump of the anode spot from the surface of the nozzle (4) onto the semi-finished product (5).

An advantage of the parallel connection of the ioniser is the possibility of using the system both for plasma and arc welding. In turn, a disadvantage of the above-presented solution is the detrimental effect of interference on the welding power source and the supply network. In order to reduce the level of high-frequency interference as well as to prevent the breakdown of the insulation and semiconductor joints in the welding power source, the oscillator should be fixed as close to the plasma torch as possible. In all of the cases, the capacitor (C) is used to protect the welding power source against the high voltage of the oscillator. If the plasma torch is significantly distant from the power source, the use of two protective capacitors is recommended, where one should be located near the plasma torch and the other at the terminals of the welding power source.

The above-presented systems can be used in plasma torches of various power:

- in high-current plasma torches, the key (K) is switched on during the excitation of auxiliary arc,
- in low-current plasma torches, the key (K) is switched on during the entire cutting process.

The function of the keys can be performed by the systems composed of passive elements presented in Figure 10.

The generator of high voltage and frequency (2) is permanently connected with two starting circuits. Treating both gaps in the plasma torch as short circuits, passive elements were selected so that, in relation to high-frequency current, the impedance of the circuit marked with the blue dashed line is significantly higher

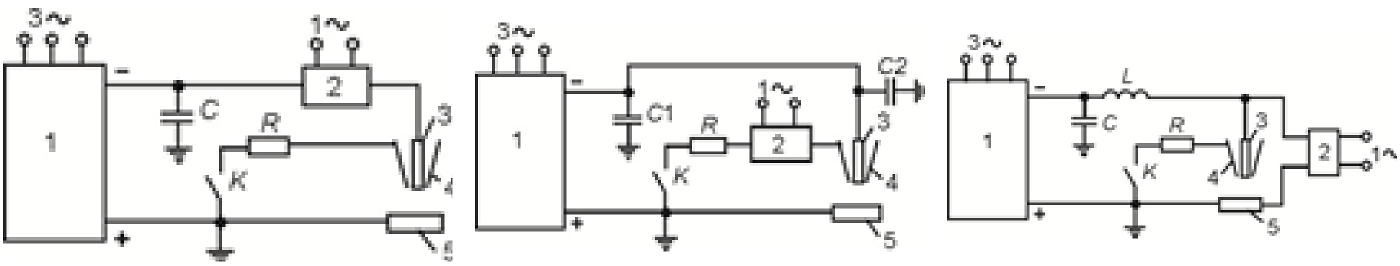


Fig. 9. Schematic diagrams of cutting plasma torch systems with the key-triggered ioniser: a) connected in series in the electrode circuit, b) connected in series in the nozzle circuit and c) connected in parallel (1 –welding power source, 2 – ioniser, 3 – cathode, 4 – nozzle and 5 – semi-finished product) [9]

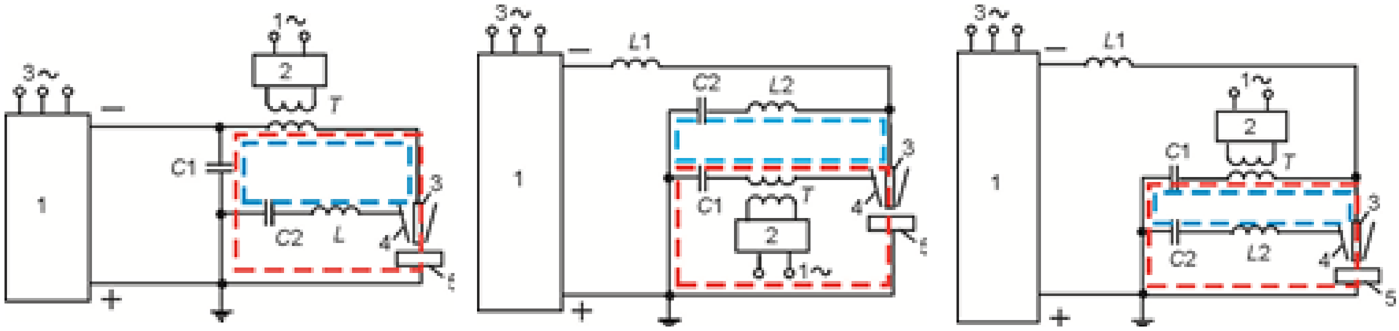


Fig. 10. Schematic diagrams of plasma torches for cutting, with the LC system-triggered ioniser: a) connected in series in the electrode circuit, b) connected in series in the nozzle circuit and c) connected in parallel (1 – welding power source, 2 – ioniser, 3 – cathode, 4 – nozzle and 5 – semi-finished product) [10]

than the impedance of the circuit marked with the red dashed line. Because of the fact that the distance between elements nos. 3 and 4 is significantly shorter than that between elements nos. 3 and 5, discharge ignition will first occur between the electrode and the nozzle. If the front of the nozzle (4) is sufficiently close to the semi-finished product (5), the impedance of the circuit marked with the red line becomes lower than the impedance of the circuit marked with the blue line and discharge ignition occurs between the cathode (3) and the semi-finished product (5).

Double arc in plasma torches with partly external arc

The overly weak stream of gas or excessively high current lead to the formation of double arc. Similarly, if the cutting rate is overly low and sheets are thin or characterised by low thermal conductivity, a wide gap (favouring the formation of double arc) is formed. In such a situation, single arc characterised by the long cathode-semi-finished product section is divided into to two smaller sections, i.e. cathode-nozzle and nozzle-semi-finished product. Because of its design and intended use, the nozzle is not adapted for such long operation and undergoes quick erosion (or even melting). As a result, the technological process is interrupted.

Double arc is usually formed during the excitation of cutting arc. Other possible reasons are the following [8]:

- drop-triggered contact of the nozzle tip with the metal subjected to cutting,
- sudden gas mass stream reduction,
- reduction of supply network voltage.

The methods preventing the nozzle-triggered formation of double arc are the following [11]:

- use of a set of nozzles characterised by the short distance of plasma compressing duct (l) in relation to diameter d,
- use of a set of nozzles with thermal insulation,
- formation of the layer of cool gas (characterised by higher electric strength) near the internal surface of the nozzle,
- use of diatomic gas admixtures,
- adjustment of the gas mass stream to current,
- adjustment of the cutting rate to the thickness of sheets and their thermal conductivity.

Plasma torches feature special systems cutting off power supply after the formation of double arc. To this end, a relay is used between the tip of the nozzle and the circuit of work current. After the termination of auxiliary arc, the relay controls current in the nozzle circuit. If plasma comes into contact with the duct in the tip of the nozzle, current in the relay switches off the arc power source.

The cutting current control unit contains the following elements:

- devices for the switching off and controlling of current at each stage of arc ignition and cutting processes,
- systems for controlling gas streams,
- systems for controlling water streams,
- systems preventing the formation of double arc,
- measurement systems for cutting parameters.

Selected welding properties of arc plasma torches

The advantages resulting from the use of plasma technologies in welding engineering are the following [11]:

- possibility of precisely locating the area of intense heat emission,
- possibility of obtaining high values of heat thermal flux density (102–103 kW/cm^2).

Depending on the power of arc and the arc melting method, there are three methods [12]:

- microplasma arc welding of metals having a thickness below 1 mm,
- plasma arc welding using arc not penetrating metals having a thickness restricted within the range of 1 mm to 3 mm,
- plasma arc welding using arc penetrating metals having a thickness above 3 mm,

Unlike argon-shielded TIG welding, plasma arc welding is characterised by the greater possibility of melting. This results in the following advantages of plasma torch applications:

- higher efficiency,
- smaller area of heat affecting the semi-finished product,
- smaller deformations of the semi-finished product during welding,
- lower consumption of shielding gases,
- higher electric arc burning stability,
- weaker correlation between weld quality and arc column length changes (resulting from the constant cross-section of the arc column in relation to its length).

The applications of microplasma torches of direct operation are the following [13]:

- welding and cutting of thin metal sheets,
- precise surfacing and repair welding of microcracks and microdefects.

The applications of microplasma torches of indirect operation are the following:

- brazing, welding and cutting of metal foils and mesh,
- surface processing of non-metallic elements,
- cutting of textiles and other fibrous materials,
- joining of wires in electronic equipment.

AC microplasma torches are used to weld thin sheets made of aluminium and its alloys. Microwelding is used in the processing of semi-finished products which are very important for the national economy and the safety of citizens. The length of arc in microwelding is usually restricted within the range of 2 mm to 8 mm (sometimes up to 20 mm).

The properties of arc in the plasma torch of indirect operation are the following:

- plasma column shape is similar to that of a needle,
- arc length only slightly affects a heat input,
- arc is more stable in the presence of magnetic fields,
- heat input is controlled easily by changes of current,
- arc can be used as independent of semi-finished product properties.

The properties of the microplasma arc welding process are the following:

- current restricted within the range of tens of microamperes to tens of amperes,
- low plasma-forming gas flow rates restricted within the range of 14 l/hour to 18 l/hour,
- shielding gas flow rates restricted within the range of 180 l/hour to 740 l/hour,
- thickness of joined metal elements ranging from tens of micrometres to 2 mm.

The comparison of microplasma arc welding involving the use of external arc with the TIG welding process indicates the following advantages of the former [12]:

- more stable arc burning in relation to low current (even below 1 A),
- narrower welds and smaller deformations of products resulting from a lower heat input,
- resistance of the welding area to initial deformations (Fig. 10),
- lower costs in comparison with laser beam or electron beam welding.

Plasma torches for cutting can be divided as follows:

- plasma torches with direct arc,
- plasma torches with indirect arc.

In terms of current, plasma arc cutting machines are divided into the following types:
- DC plasma arc cutting machines,
- AC plasma arc cutting machines.

In relation to cutting methods, plasma arc cutting machines are divided as follows:
- plasma torches used in manual cutting – characterised by small dimensions and used in technologies applied in small-scale production. Even plasma torches having relatively low power can be used for the cutting of semi-finished products made of metal and having a thickness of up to 30 mm (e.g. plates, tubes and various structures);
- plasma torches used in automated cutting – applied in stationary numerically-controlled machines (e.g. for automated cutting of metals). Usually, such plasma torches are used with several types of exchangeable nozzles.

As regards types of gases used, plasma arc cutting machines are divided into the following types:
- plasma arc cutting machines using compressed (regular or purified) air – the most popular type of plasma torches; their primary advantages include simple design, low running costs and easy control;
- plasma arc cutting machines using argon, oxygen or nitrogen – applied in very complicated systems and large robotic numerically-controlled machines; these plasma torches are used to cut non-ferrous metals and their alloys. In comparison with plasma torches using air, plasma torches using argon, oxygen or nitrogen require precise tuning;
- plasma arc cutting machines using steam, where water is used as a medium cooling plasma torch elements. Exposed to high temperature, water undergoes evaporation, dissociation and ionisation and becomes highly enthalpic gas.

In relation to the type of arc ignition, plasma arc cutting machines are divided as follows:
- plasma arc cutting machines with contact (lift) ignition; a contact is necessary between the nozzle and the semi-finished product (before arc appears between them). The moving (lifting) of the torch and the ignition of initial arc are followed by the jump of initial arc from the nozzle onto the cathode.
- plasma arc cutting machines with pneumatic ignition (PN). Inside the plasma torch there is a contact between the electrode and the nozzle (before arc appears between them). Compressed air moves the electrode or the nozzle away, thus enabling the formation of initial arc.
- plasma arc cutting machines with high-frequency ignition (HF). Arc is generated using the oscillator. It is only formed during high-frequency discharge between the torch and the semi-finished product surface. Initial arc is formed on operator's demand; primary arc appears automatically when the nozzle nears the semi-finished product.

In relation to the cooling method, plasma arc cutting machines are divided into the following types:
- air-cooled plasma arc cutting machines, where the nozzle is cooled by gas or working air flowing through it;
- liquid-cooled plasma arc cutting machines; liquids are used to cool high-power machines (using a current of more than 150 A).

Arc used in plasma arc cutting processes is characterised by the following features:
- variable length,
- variable cross-section,
- significant inhomogeneity of the chemical composition of plasma in relation to length,
- significant inhomogeneity of current density in relation to length.

The advantages of plasma arc cutting machines are the following:
- high power and efficiency of processes,
- high quality of material processing,
- versatility,
- safety,
- environmental friendliness.

The disadvantages of plasma arc cutting

machines include:
- high purchase cost,
- limited thickness of a semi-finished product subjected to cutting,
- impossible simultaneous operation of two plasma arc cutting machines powered by one welding power source.

Figure 12 presents areas representing the effect of a given technology on the cutting rate related to steel sheets/plates of various thicknesses. As can be seen, the aforesaid areas are of various widths and partly overlap one another. Plasma cutting can be performed in relation to vast ranges of thicknesses and cutting rates. The process depends not only on current, but also on the type of plasma-forming gas.

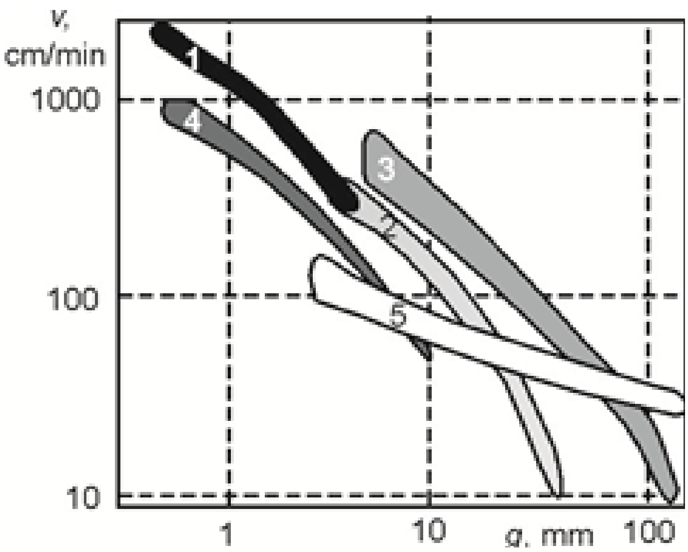


Fig. 12. Effect of technologies on the cutting rate (v) of steel sheets/plates of various thickness (g) (1 – 400 A oxygen plasma, 2 – 200 A plasma, 3 – 600 A plasma, 4 – laser having a power of 1000 W/1500 W and 5 – oxygen fuel) [14]

Single-component gases presented below are characterised by the following properties [11]:
- nitrogen – low cutting rate and quality,
- argon – poor cutting results, high cost,
- helium – very high price,
- oxygen – problematic obtainment of long cathode service life,
- hydrogen – short service life of the plasma torch nozzle.

The use of argon is the least favourable as, with the same mass stream of another gas, there is a condition of double arc:

$$\max\left(\frac{l}{d}\right)_{Ar} << \max\left(\frac{l}{d}\right)_{gas}$$

where l – nozzle duct length, d – nozzle duct diameter.

The most favourable gas is hydrogen (sometime used with other gases as an admixture). The rate of cutting depends on the concentration of hydrogen. An addition of oxygen results in the chemical effect of oxygen on metal subjected to cutting. The use of steam enables the use of both gases at the same time (and, in fact, is applied in plasma arc cutting machines).

The cutting of metals usually involves the use of air-plasma arc. Metal surfaces are also directly affected by electric current. The principle of plasma torch operation includes:
- melting of metal,
- blowing liquid metal out of the cutting zone.

Plasma arc cutting systems consist of the following components:
- electric arc power supply source, e.g. welding transformer or inverter,
- plasma arc cutting machine, referred to as the plasma torch,
- compressor,
- cables.

The stream of gas flowing through a narrow nozzle translates into [12]:
- spatial stabilisation and compression of arc,
- higher efficiency of convective transfer of heat from the arc column to the semi-finished product,
- suppressing or blowing molten metal out of the welding tank,
- heating and acceleration of particles provided to plasma (e.g. spraying/deposition of coatings).

The advantages of plasma torches are the following:
- possibility of processing all metals and their alloys,
- high equipment efficiency,
- high precision, enabling even cutting without allowances and losses,
- no need for the preheating of semi-finished

products,
- no need for the use of hazardous/explosive gases (methane, oxygen).

The advantages of the plasma arc hardening process are the following [12]:
- easy location of the technological process,
- significant steel hardening depth,
- high efficiency,
- possibility of performing the process in various gaseous environments and in vacuum,
- possibility of process automation and robotisation.

The advantages of the plasma arc surfacing process are the following [12]:
- possible control of the composition, structure and properties of overlay weld metal,
- high efficiency,
- low tungsten electrode consumption,
- small allowance for the product surface,
- possibility of using normal and reversed polarity,
- low residual stresses and small deformations,
- ease of mechanisation and automation.

The power of DC plasma torches can be adjusted using [15]:
- current (in the welding power source)
  - advantages – easy to obtain by changing the appropriate setting of the welding power source,
  - disadvantages – necessity of increasing the nozzle diameter, leading to greater cutting widths and shorter plasma torch service life,
- voltage (by changing the length of arc)
  - advantages – normal (i.e. not increased) consumption of electrodes, unaffected cutting width and power source operating conditions,
  - disadvantages – necessary changes in the composition of plasma-forming gas, gas mass stream, nozzle diameter and length, geometrical dimensions of the chamber and pressure inside it as well as the distance between the torch and the workpiece (potentially affecting the cutting of thick materials and cutting rate values).

The thermal efficiency of compressed arc can be controlled by changing [12]:
- arc current,
- gas mass stream and composition,
- nozzle diameter,
- distance between the nozzle and the semi-finished product.

Concluding remarks

1. In welding equipment with free arc, arc discharge ignition is usually a one-stage process. In turn, in most devices with compressed arc, arc discharge ignition is a two or multi-stage process.

2. The improper operation of the ioniser in welding machines with free arc leads to the discontinuation of the technological process. In turn, in most welding machines with compressed arc, the improper operation of the ioniser could also damage the plasma torch.

3. In welding machines with compressed arc it is recommended to use automatic ignition systems to reduce the probability of damaging the plasma torch.

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