Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 24, 2012, Sofia

PULSE–ARC PLASMA WELDING AND SURFACING PROCESSES

Rayna Dimitrova, Bojana Tabakova

Technical University of Sofia

Abstract
The paper presents literature survey on pulse-arc plasma welding and surfacing processes. Some issues related with these processes' equipment and materials, variations, application, technologies, and the quality of the welded workpiece are considered.

Introduction

Plasma processes use thermal plasma energy to melt material. The attempts to achieve higher energy density by constricting the electrical arc date a long way back. One of the earliest plasma arc systems was the gas vortex stabilization device introduced by Schonherr in 1909. In this device, gas was fed tangentially into an arc-discharge tube.

In 1922, Gerdien and Lotz designed an arc-stabilizing device by injecting tangentially water to the tube centre. Water whirled along the internal surface and was ejected in the ends. When the arc burned between carbon electrodes and passed through this tube, the water concentrated the arc along the axis, causing high current density. The term *thermal plasma* was first introduced in 1927 by the American physicist Langmuir to denote the fourth aggregate state of matter, i.e. the state of a gas with high dissociation and ionization rate, which apart from neutral atoms and molecules, contains positive and negative charges – ions and electrons. In 1961, the first plasma surface processing equipment was presented, and in 1963, the first plasma welding was introduced.

Peculiarities and characteristics of plasma welding and surfacing

Plasma welding is, in substance, a development of the TIG welding process, however using a different mechanism to transfer thermal energy to the workpiece. Both TIG and plasma welding use a non-melting (tungsten) electrode located in a nozzle, through which the plasma-forming gas is passed. The arc heats this plasma-forming gas, which gets ionized, attains electric conductivity, and is forced out through the nozzle. This ionized gas is defined as plasma. The plasma jet leaves the nozzle at temperature of about 16,700°C (30,000°F) in the form of constricted concentrated jet with precisely controlled direction, which creates a highly favourable seam form coefficient (pool depth-to-width ratio).

Compared to the TIG-arc, plasma features:

- exceptionally high thermal power, energy density, and temperature of the plasma arc;
- cylindrical form of the arc;
- high kinetic energy of the exiting plasma jet;

At low plasma kinetic energy, the melted metal is not blown away, which provides favourable conditions for the welding or surfacing technological processes.

Plasma surfacing is used to lay various metals or alloys on the details' surfaces to improve their operational properties. The laid on metals or alloys feature great hardness, wear-resistance, corrosion resistance and thermal resistance. The depth of the surfaced layer in a passage may reach 4-5 mm. Surfacing in several layers is possible. The process provides to obtain high-quality details with insignificant spending of expensive alloy materials.

Plasma surfacing is applied to lay copper, bronze, or other special alloys on the working surfaces of steel vapour-conducting fixture elements, chromium-nickel alloys covering internal combustion engine valves and more. The process is used successfully during the repair of stamps, press-forms, rolling rolls, and other metal-processing equipment elements.

Plasma welding and surfacing are arc processes, in which the common metal pool is obtained as a result of a forcedly constricted arc between a non-melting electrode and the workpiece (direct arc) or between a non-melting electrode and a concentrating nozzle (indirect arc). No pressure is applied on the welding pool. The process may be implemented with or without additional metal. The arc is concentrated in an ionized plasma column exiting the nozzle's end (Fig. 1).

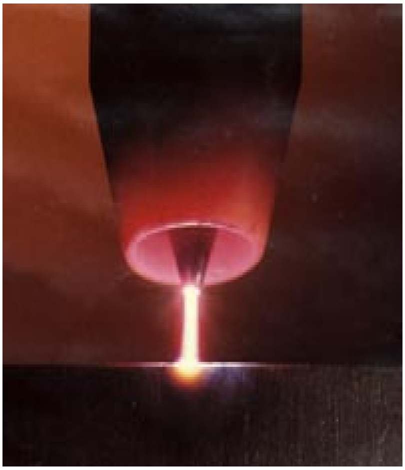

Fig. 1

The plasma-forming gas also provides protection to the molten metal and usually constitutes a part of the basic protection gas, which may be inert gas or inert gas mixture. The gas mainly used as plasma-forming gas is argon. Argon gets easily ionized and therefore provides for the arc's easy ignition. By adding molecular gases (H_2 and N_2), the thermal content of the plasma-forming gas may be increased significantly compared to pure argon (under the same temperature). When the hot gas collides with the relatively colder surface of the workpiece, as a result of atom and ion recombination, the heat from dissociation and ionization is given out accordingly. Thus, the arc's stability is improved and the invested heat amount and the arc's penetration depth into the processed workpiece is increased.

Plasma arc is used to weld non-rusting steels, nickel alloys, titanium alloys, molybdenum, tungsten and more. Compared to TIG welding, the process features a more stable arc and more uniform weld penetration depth. According to its penetration ability, the method occupies intermediate place between electric-arc and electron-beam welding. The arc's column has cylindrical form; therefore, the width of the heated surface depends poorly on the arc's length. The plasma arc provides to obtain heat spot with constant diameter, which results in stabilization of the weld penetration depth. This is particularly important in thin tin welding. The change in the heat spot form is accomplished by using nozzles with different structure (Fig. 2).

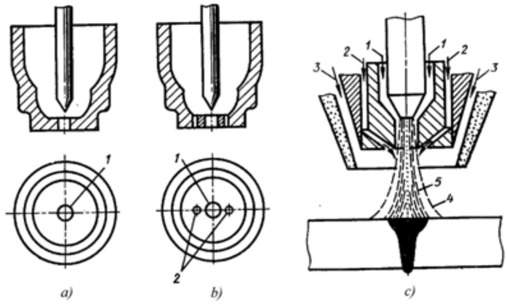

Fig. 2

For instance, when it is necessary to obtain an elongated heat spot in the nozzle (Fig. 2b), two additional openings are made through which cold plasma-forming gas exits, thus reducing the spot's cross size. The use of such a nozzle reduces HAZ's width and increases welding rate by up to 50÷100%. Another variety in the nozzles with additional openings is the formation of a focusing gas flow (Fig. 2c) which constitutes gas mixture consisting of. Ar and He or Ar and H_2, gets ionized with greater difficulty and thus constricts plasma.

Plasma-forming gas is fed tangentially, which provides for proper arc stabilization using a small capacity. Focusing gas is fed through a concentric ring-like channel located between the channels of the plasma-forming gas and the protective gas. Focusing flow is fed at an angle with respect to the arc's longitudinal axis which results in additional constriction of the arc as a result of its cooling. Another possibility for deformation of the heat spot is to use non-homogeneous magnetic field.

Types of plasma arcs and plasmatrons

Depending on the manner of their generation, three main types of plasma arcs and accordingly, three plasma processes may be identified, which are implemented by the respective plasma generation devices, i.e. plasmatrons:

- plasma–arc process with open arc (direct, shifted arc);
- plasma–jet process with closed arc (indirect arc);
- plasma–jet–arc process with open and closed arc – combined process;

Plasma–arc process with open arc (direct, shifted arc)

During open-arc welding 8 (Fig. 3.) the tungsten electrode is cathode 4 and the workpiece is anode 6. The arc passes through water-cooled nozzle 7, whereat it gets constricted. Argon is used as plasma-forming gas which, depending on the processed metal, may also contain hydrogen (5÷10% for high-alloy Cr-Ni steels) or helium (for Ti and Zr).

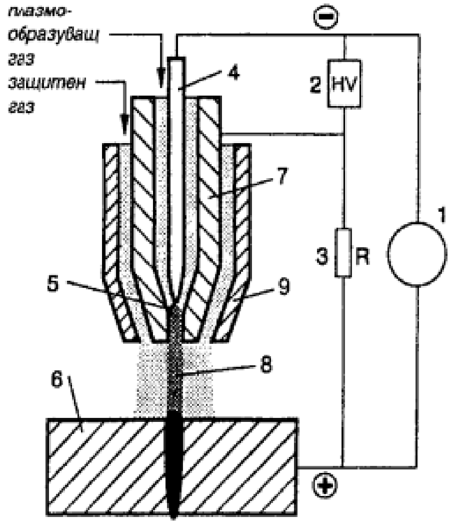

Fig. 3

Plasma-forming gas is fed concentrically around the tungsten electrode, thus also protecting it from oxidation. To provide for the arc’s lighting, voltage is applied on the internal nozzle, too. Through high-voltage pulses HV from device 2, the auxiliary (pilot) arc 5 between tungsten electrode 4 and copper nozzle 7 is ignited. To prevent the possible melting of the copper nozzle, resistance R (3) is been included in the current loop of the pilot arc. The pilot arc ionizes the plasma-forming gas, after which main arc 8 jumps onto the workpiece. After the arc has transferred to the base metal, the auxiliary arc is switched-off. Protective gas both protects the welding area and cools the arc column. In some cases, additional concentric jet of cooling gas is let out. The cooling of the arc’s column results in its constriction and increase of the thermal source’s concentration. As a result, current density around the arc’s longitudinal axis increases and the temperatures along the axis of the arc’s column reach 3,000K. This provides to weld without flanging widths much greater than those welded after the TIG method. Moreover, linear energy is much smaller and welding rate is up to several times greater. All this has quite a favourable impact on deformations during welding, which

are usually negligibly small. Cooling rates in HAZ are greater and this should be accounted for in welding materials tending to form tempered structures.
To protect the melted area from ambient temperature, additional protective gas is used – 99.95% Ar. It is fed concentrically between the copper nozzle and the gas nozzle. To prevent plasma jet expansion after its exiting the nozzle, additional focusing gas may be used.
During welding of mild steels or low-alloy steels, carbon dioxide may be used as protective gas. On account of the relatively narrow heating area, the deviation of the burner (plasmatron) (Fig. 4) from the seam's line should not exceed 10% of the welded thickness.

Fig. 4

The composition of the protective gas affects the penetration ability of the arc. The addition of hydrogen to argon increases the weld penetration depth. The optimal concentration is 7%. When using helium, the weld penetration depth is smaller compared to argon-hydrogen mixture. In contrast to the TIG process, during welding of stainless steels, the addition of 7.5% hydrogen to the protective gas does not cause formation of pores
During plasma welding, butt seams with sheet material thickness of up to 9.5mm may be implemented without flanging the ends and without using additional metal. With thickness of up to 25mm, V- or U–shaped flanging is required, whereas the flanging angle is smaller compared to the TIG process. The additional metal quantity is reduced up to three times. The process has greatest advantages in welding without flanging. During plasma welding, the additional metal is fed in the back part of the welding pool. The process may be used in all spatial applications and different mechanization levels. Among its various applications, it displays one of its greatest advantages in pipe welding.

Plasma–jet process with closed arc (indirect arc)

The closed arc 5 (Fig. 5) burns inside the plasmatron between tungsten electrode 4 and water-cooled copper nozzle 7. Therefore, only a plasma jet exits the plasmatron. The plasma jet is characterized by a bright-glowing nucleus having a base a little less the size of the nozzle's opening. The nucleus is surrounded by a torch with weaker light emission. The jet length is determined by the arc's power, the nozzle's diameter, and the gas capacity. In case of lamellar exit of the gas, the jet is long and actually, it does not mix with the surrounding environment. In case of turbulent exit of the gas, a short plasma jet is observed. By varying the nozzle's form, the contour of the plasma jet may be preset, thus affecting the distribution of the jet's thermal and power impact on the processed material. The temperature field in the jet is characterized by great radial and axial gradients, reaching temperatures of 32,000^{0}C near the cathode.

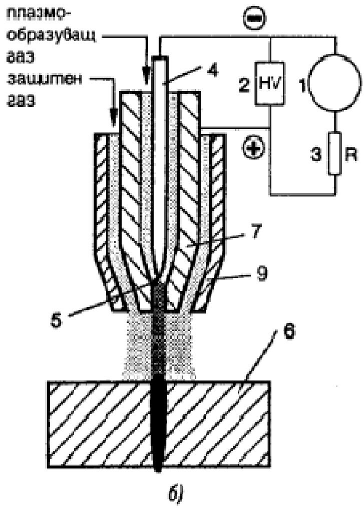

Fig. 5

In engineering practice, plasma jet is characterized by the average mass temperature in the cross section coinciding with the nozzle's butt plane. It may be determined by the relative enthalpy of plasma-forming gasз $H = q/G$ (q is the effective arc power in this plane, J/s; G is the mass capacity of plasma-forming gas, g/s. Table 1 contains the main parameters of the plasma jet for some gases used in practice.

Table 1

Plasma-forming gas	Arc power, KW	Gas capacity, g/s	Internal coefficient of performance (COP) of the plasmatron	Relative gas enthalpy, kcal/m^3	Average mass temperature of the plasma, K
Nitrogen	25	0.5	60	9000	7350
Hydrogen		0.1	80	4350	4075
Air		0.5	50	7760	6925
Argon			40	8450	14100

The main parameters regulating plasma jet thermal characteristics are: current magnitude, plasma-forming gas capacity, and arc length. Their impact on average mass temperature and jet power is shown in Fig. 6

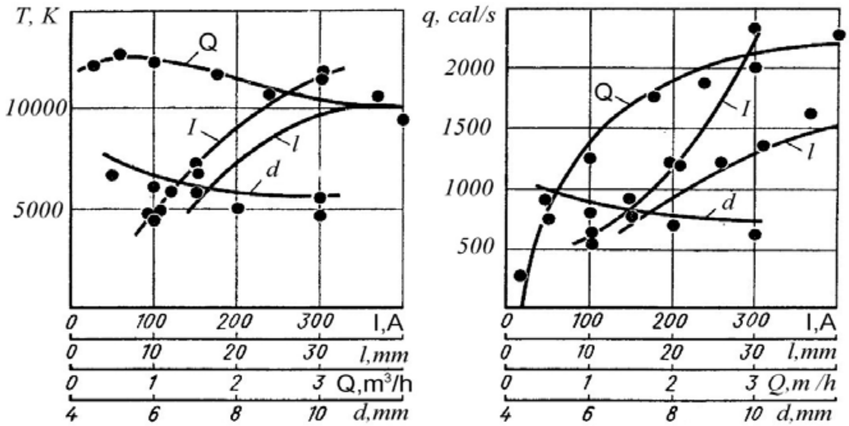

Fig. 6. Impact of the main parameters of the mode: current magnitude I (l=30mm, Q=2.35m^3/h, d=8mm), arc length l (I=200A, Q=2.35m^3/h, d=8mm), argon capacity Q (I=200A, l=30mm, d=8mm), and nozzle diameter d (I=200A, Q=2.35m^3/h, l=30mm) on average mass temperature T and thermal power q

As a result of convective and radiation heat removal, the effective thermal power of the plasma jet q_e is less than q. Increase of current magnitude and decrease of nozzle diameter result in its increase. When plasma-forming gas capacity is small, its increase results in sharp power increase, while with high capacity values its increase actually does not affect power.

Increasing the distance between the nozzle and the heated plane decreases effective power as a result of the increased losses. Convective heat removal increases with turbulent jets. This explains the sharper reduction of effective power with increased capacity. In case of interaction of the plasma jet with a surface perpendicular to its axial axis, thermal flow distribution is close to normal (Fig. 7).

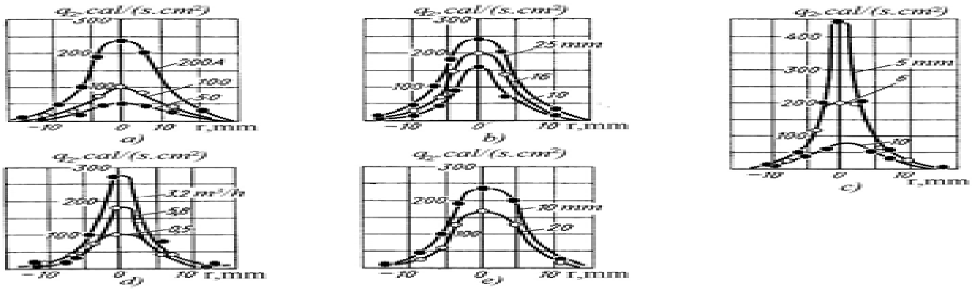

Fig. 7. Impact of current magnitude (a), arc penetration into the nozzle (b), nozzle diameter (c), argon capacity (d), and distance between the nozzle and the workpiece (e) on thermal flow distribution

The maximal density of the thermal flow (q_2) may change from values equivalent to gas flame to values corresponding to a welding arc. It increases with increase of current and arc length and decrease of nozzle diameter. Apart from the thermal impact, plasma jet also has noticeable power impact on the processed material (Fig. 8).

Plasma–jet–arc process with open and closed arc – combined process

The plasma–jet–arc process is implemented by combining open and closed arc in the same plasmatron. Here, two separately regulated direct current sources are used (Fig. 9). One powers closed arc 5 between tungsten electrode 4 and copper nozzle 7, and the other powers open arc 8 between the electrode and the workpiece. In contrast to the open-arc plasmatron, in this case both arcs burn simultaneously and continuously during the entire welding process. Thus, the closed arc stabilizes further the process and, together with the strongly compressive action of anode nozzle 7, it supports the stable burning of the open arc even at very low current magnitudes. Combined plasmatrons are suitable for both welding and surfacing.

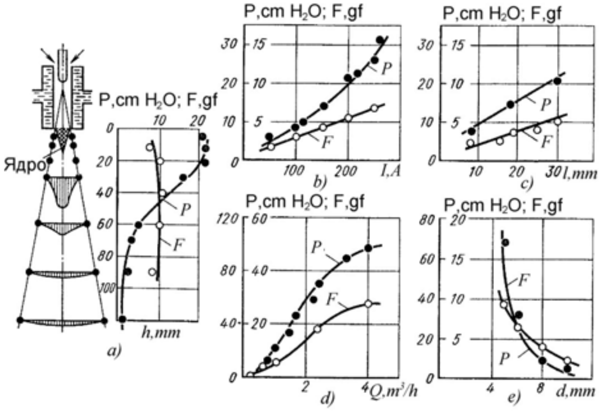

Fig. 8. Impact of the parameters on the pressure along the jet axis and the overall power impact (a – distance to nozzle b – current magnitude, c – arc penetration, d – argon capacity, e – nozzle diameter)

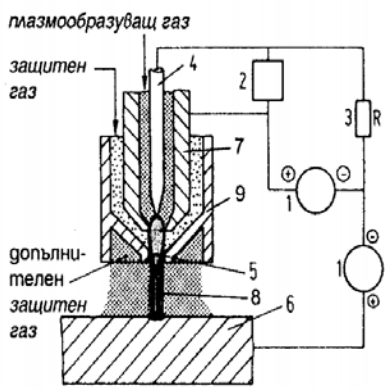

Fig. 9

The analysis of the publications in this field reveals numerous versions of the plasma welding and surfacing technological process:

- using additional material: powder or wire; moreover, wires may be one or two, with solid or tubular cross-section;

- single-arc or double-arc, whereas the arc may burn on the workpiece or on the welding wire, while with the double-arc process one arc burns on the workpiece and the other one burns on the wire or on the canal of the plasma-forming nozzle;
- the polarity of the direct-acting arc may alternate between direct and reverse, depending on the used electrode types;
- usually, argon or argon-hydrogen mixture is used as both plasma-forming and protective gas, but some combinations may be also used, such as: argon as plasma-forming gas, CO_2 – as protective gas;
- depending on the workpiece's complexity and size, surfacing may be implemented manually or by a mechanized process;
- mechanized surfacing may be implemented with no transverse oscillations or with oscillations of various trajectories;
- high-speed plasma surfacing;

Conclusion

The current technology development level, the economic situation, the dynamically changing user needs and requirements impose the need of manufacturing or restoring complex and precise articles within increasingly short time limits and with reduced production costs. An essential trend in the economy of spare parts, raw materials, materials and energy is the introduction of competitive industrial technological processes. Pulse–arc plasma processes have significant potential to produce new high-quality articles, or to repair or restore old ones.

References

1. A n a w a, E. M, A. G. O l a b i. Using Taguchi method to optimize welding pool of dissimilar laser-welded components. Optics & Laser Technology, Volume 40, Issue 2, 2008.
2. A s h b y, M. F., H. S h e r c l i f f, D. C e b o n. Materials: engineering, science, processing and design. Butterworth-Heinemann, 2007.
3. B e r n s H a n s, Microstructural properties of wear-resistant alloys. Wear, Volumes 181-183, Issue 1, 1995.
4. F i s c h e r, A. Well-founded selection of materials for improved wear resistance. Wear, Volume 194, Issues 1-2, 1996.
5. F o u i l l a n d, L., M. E l M a n s o r i, M. G e r l a n d. Role of welding process energy on the microstructural variations in a cobalt base superalloy hardfacing. Surface and Coatings Technology, Volume 201, Issue 14, 2007.

6. G a r c i a – A l l e n d e, P. B., J. M i r a p e i x, O. M. C o n d e, A. C o b o, J. M. L o p e z-H i g u e r a. Spectral processing technique based on feature selection and artificial neural networks for arc-welding quality monitoring. NDT & E International, Volume 42, Issue 1, 2009
7. H o u, R., D. M. E v a n s, J. M c C u r e, A. C. N u n e s, G. G a r c i a. Shielding gas and heat transfer efficiency in plasma arc welding. Welding Journal.Jia Chuan-bao, Wu Chuan-song, 1996.
8. L i u L i m i n g, H a o X i n f e n g. Improvement of laser keyhole formation with the assistance of arc plasma in the hybrid welding process of magnesium alloy. Optics and Lasers in Engineering, Volume 47, Issue 11, November 2009.
9. O b e r h e u s e r, G. Wear protection of surfaces from high pressure grinding rolls: possibilities and limits. International Journal of Mineral Processing, Volumes 44-45, 1996.
10. P a l a n i, P. K., N. M u r u g a n. Selection of parameters of pulsed current gas metal arc welding. Journal of Materials Processing Technology, Volume 172, Issue 1, 20 February 2006.
11. Weldind Handbook Ninth Edition, vol. 2, Welding Processes, Part 1, 2004.
12. Z h a n g Y u-m i n g. Sensing controlled pulse key-holing condition in plasma arc welding. Transactions of Nonferrous Metals Society of China, Volume 19, Issue 2, April 2009.
13. В а с и л е в, В. Технология на възстановяване на детайлите. Русе, 1996.
14. Г у д р е м о н, З. Специальные стали Tl. M. : Металлургия, 1966.
15. Ж е л е в, А. Н. Комплексен термодинамичен подход за оценяване горещата трошливост на металите при заваряване. Дисертация за получаване на научна степен „Доктор на техническите науки", София 1989.
16. Ж е л е в, А. Материалознание, техника и технология, Том II, Технологични процеси и обработваемост, София, 2003.
17. Л о л о в, Н. В. Заваряемост на металите, Част 1: Физични процеси., София 1995.
18. Технология злектрической сварки металлов и сплавов плавлением. Под ред. Б. Е. Патона, Москва, Машиностроение, 1974.
19. Т о н г о в, М. Заваряване, Част Първа, Процеси, София, 2009.

ИМПУЛСНО-ДЪГОВИ ПЛАЗМЕНИ ПРОЦЕСИ ЗА ЗАВАРЯВАНЕ И НАВАРЯВАНЕ

Р. Димитрова, Б. Табакова

Резюме

Направен е кратък обзор по литературни данни на импулсно-дъговите плазмени процеси за заваряване и наваряване. Разгледани са въпроси, свързани с оборудването и материалите, различните вариации на тези процеси, тяхното приложение, технологии за заваряване и наваряване, както и качеството на завареното изделие.