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TECHNOLOGICAL PARAMETERS AND QUALITY CONTROL WHILE DIFFUSION WELDING IN A GLOW DISCHARGE

The main parameters of diffusion welding and the features of their control methods are described. It is shown that, under conditions of diffusion welding with heating of parts in a glow discharge plasma, traditional methods of monitoring the temperature state of the welding zone such as thermocouples and optical pyrometers become insufficiently effective due to interferences caused by the specific characteristics of the glow discharge, namely, the presence of a strong electric field on the surface of the parts and plasma radiation. Under these conditions, it is more appropriate to use selective temperature control methods, particularly photoelectric pyrometers whose maximum spectral sensitivity lies in the infrared region of the electromagnetic spectrum emitted by the welded part. An effective and promising method for monitoring the thermal state of the welding zone for bodies of various shapes and dimensions is the use of deterministic mathematical models based on the fundamental laws of thermophysics.

***Keywords**: Diffusion welding; glow discharge; plasma; technological parameters; quality control.*
Fig.: 9. References: 24.

Urgency of the research. Diffusion welding process is widely and effectively used to obtain precision permanent joints for both homogeneous and heterogeneous materials. In diffusion welding, the joint formation occurs in the solid state and is determined by three main parameters that must be carefully controlled. These parameters include the heating temperature (T_h), the compression force (P), as well as welding time (t) [1].

The heating temperature of the welding zone should be T_h = 0.6 – 0.8 of the melting temperatures of the most fusible material in the welded assembly. Heating ensures both an increase in the rate of diffusion processes and the plasticity of materials in their contact zone.

The compression force (P) is intended to ensure a tight contact between the joined surfaces as a result of their limited plastic deformation. This also facilitates diffusion and recrystallization processes in the welding zone.

The welding process duration (t), under constant temperature and compression force, is mainly determined by the time required for the completion of diffusion processes in the contact zone of the joined materials and normally ranges from 10 up to 30 minutes [2; 3].

Target setting. The most important parameter of diffusion welding is the heating temperature in the contact zone of the joined materials. The main result of increasing the temperature of a solid body is an increase in the rate of atomic diffusion. This applies to both self-diffusion and impurity diffusion of alloying element atoms (hetero diffusion) [4]. The rate of physical and chemical changes occurring through diffusion can be significantly increased by a relatively small temperature rise. For instance, the diffusion coefficient of indium atoms in a nickel substrate increases by two orders of magnitude (from 10^{-21} to 10^{-19} m²/s) when the substrate temperature rises about 100 K (from 798 up to 886 K) [5].

When the welding temperature decreases, not only the atomic diffusion processes are inhibited, the cleaning of the contacting material surfaces from oxides and contaminants by sublimation becomes difficult, and the deformation of surface roughness micro protrusions at the stage of forming the physical contact also does. Moreover, under such conditions, recrystallization processes which lead to the formation of common grains in the welding zone and are essential for obtaining a high-quality joint do not develop sufficiently [6].

At the same time, experimental data has shown that the dependence of diffusion weld strength on the welding temperature has an extreme character (see Fig. 1) [7] that is the maximum strength of the joint is achieved within a rather narrow temperature range. This is because an excessive increase in welding temperature, while accelerating diffusion processes, also causes grain growth during the welding of homogeneous metals or the formation of intermetallic compounds when welding dissimilar materials. The latter significantly deteriorates the mechanical properties of the joint has been weld. These factors make it necessary to carefully control the thermal mode of the joint zone while welding.

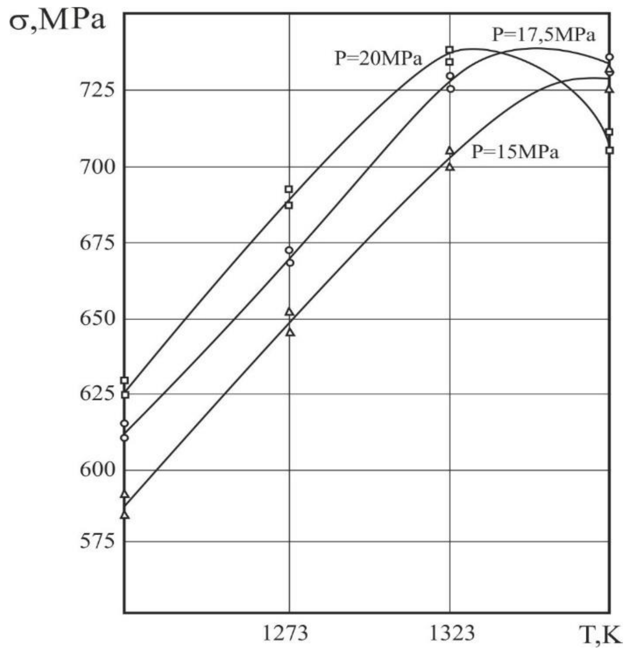


Fig. 1. Influence of Temperature and Compression Force on the Strength of the S66009 Steel Joint [7]

Actual scientific research and issues analysis. The temperature of diffusion welding must exceed the recrystallization temperature of the metals being joined and constitute a certain fraction of their melting temperature (the homologous temperature). The optimal heating temperature for each welded composition is generally determined experimentally. However, determining the optimal temperature also requires the use of appropriate temperature control methods and techniques.

Historically, the first and still traditional methods of heating workpieces during diffusion welding have been radiative and inductive (high frequency) heating [8; 9]. These methods are quite different in how heat is introduced into the materials being welded. The radiative heating source is surface based, while inductive heating is subsurface. However, temperature control during diffusion welding is typically performed on the surface of the workpieces in the contact zone, primarily due to the design features of the welded components.

In the above-mentioned heating methods for diffusion welding, traditional temperature control techniques commonly used in many industries are also applied. These methods can be divided into contact and non-contact categories. In the first case, thermoelectric converters (thermocouples in particular K-type) are used, with the hot junction required to maintain reliable contact with the side surface of the metal in the welding zone by any suitable means. The accuracy of temperature measurement depends primarily on the reliability of this contact [10].

The distinctive feature of diffusion welding is the wide variety of welded components, both in shape and size. This diversity makes it impossible to establish uniform approaches to the issue of thermocouple attachment. Nevertheless, this control method is widely used in diffusion welding since thermocouples are highly sensitive, simple in design, and reliable in operation [11].

When the shape of the welded part does not allow for reliable contact with a thermocouple, non-contact temperature control methods using optical pyrometers are come into a play [12]. These devices respond to the monochromatic radiation produced by the thermal flux emitted by the heated body. The maximum sensitivity of optical pyrometers lies within the visible spectrum of electromagnetic waves from 0.4 up to 0.76 μm [13]. Monitoring of the workpieces` temperature is carried out through the viewing window of the vacuum chamber. Optical pyrometers with a reference tungsten filament that visually disappears when its brightness matches that of the heated surface (e.g., OPPIR-09, OPPIR-017) are used. The external view of OPPIR-017 is given in Fig. 2. Temperature measurement is carried out by visually comparing the brightness of the glowing filament with that of the heated surface, which introduces a certain subjectivity in measurement accuracy and limits the applicability of this method to temperature ranges where visible glow of the workpiece occurs (typically above 1073 K).

Fig. 2. The external view of optical pyrometer OPPIR-017

Uninvestigated aspects of the main problem. Recently, a new heating method in a glow discharge plasma has been actively developed and applied in diffusion welding. This technique offers significant technological and economic advantages over traditional methods [14; 15]. It is based on different physical principles rather than conventional methods and, accordingly, has its own limitations in the control of key technological parameters.

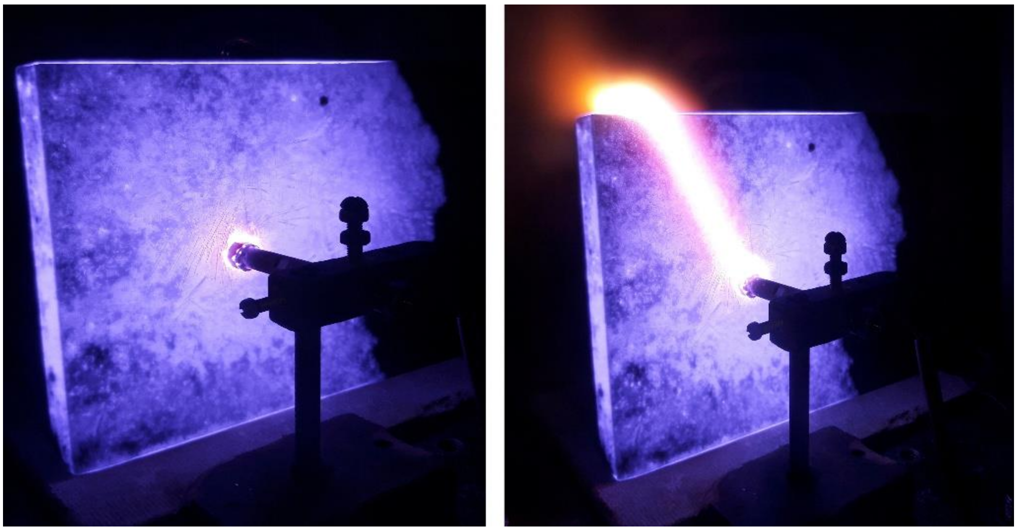
While long-term use of traditional diffusion welding methods has led to well-established approaches to process control and regulation, welding in a glow discharge lacks such practical experience and therefore requires of meticulous analysis.

The research objective. The purpose of current work is to analyze the physical properties of glow discharge under diffusion welding conditions and based on this analysis, to determine methods for controlling the technological parameters of the process and the features of their application.

The statement of basic materials. During diffusion welding, a glow discharge burns in a plasma-forming gaseous medium at a pressure of 1 – 10 kPa between two electrodes – an anode (rod or contour-type) and a cathode, which, in this case, acts as the welded workpiece itself [16]. The thermal energy is transferred from the glow discharge to the workpiece through the discharges` cathode spot, located on its lateral surface. Directly near the cathode (the workpiece) region the cathode fall of potential, which is covered above by a negative glow layer is placed. Beyond this layer follows the positive column of the plasma discharge [17].

A distinctive feature of the cathode fall region is the high intensity of the electric field reaching up to 10^5 V/m [18], which ensures the gas ionization necessary for the existence of the glow discharge.

Under these conditions, placing the hot (working) junction of a thermocouple on the surface of the workpiece distorts the shape of this surface, which in turn leads to distortion of the electric field in the near-cathode region of the discharge, accompanied by a local increase in field strength. Analysis of this factor, presented in [18], shows that under such conditions, the electric field intensity in the cathode fall region may reach up to 10^9 V/m as gas pressure increases. At this field strength, auto-electronic emission can occur, resulting in a significant local increase in gas ionization and the formation of a high-conductivity channel where an electric arc develops (see Fig. 3).



a *b*

Fig. 3. Stable glow discharge on the surface of the workpiece (a); formation of an arc discharge at the location of a thermocouple attached to the surface (b)

The arc acts as a highly concentrated energy source capable of causing melting and destruction of the thermocouple. Therefore, the use of contact methods for monitoring the welded samples temperature during diffusion welding in a glow discharge is limited and can only be recommended at low gas pressures in the reactor, or in cases where the thermocouple can be placed in a location inaccessible to the discharge (e.g., inside cavities during external heating, and vice versa).

Certain difficulties also arise when using non-contact temperature measurement methods to determine the temperature in the contact zone of parts during welding in a glow discharge. The main problem is the possibility of optical interference due to illumination of the pyrometer by the plasma radiation of the discharge. Plasma radiation occurs because of various types of interactions between charged particles. Several types of plasma radiation can be distinguished, each corresponding to a specific part of the electromagnetic spectrum [19].

Bremsstrahlung (braking radiation) (P_B) occurs when a free electron passing through the field of an atom or ion changes the direction or magnitude of its velocity, losing part of its kinetic energy in the form of electromagnetic radiation quanta. The power of braking radiation emission per unit volume of plasma can be defined as follows [19]:

$$P_B = 1.47 \cdot 10^{-26} n_e n_u z^2 \cdot (T_e)^{\frac{1}{2}}, \tag{1}$$

where n_e, n_i – concentration of electrons and ions in the plasma, cm^{-3}; Z – ordinal number of the element (gas) in the periodic table of elements; T_e – temperature of electrons (electron gas), K. The energy of electrons, and their temperature (electron energy E = 1 eV corresponds to an electron temperature T_e = 11600 K) accordingly, depends on the gas pressure (Fig. 4) and decreases with it goes up [20]. In practice, the energy of plasma electrons can vary within a wide range, therefore, bremsstrahlung may produce a continuous spectrum of electromagnetic waves. However, when the electron energy is below 1 eV, the main portion of the radiation energy lies within the visible and infrared regions of the spectrum.

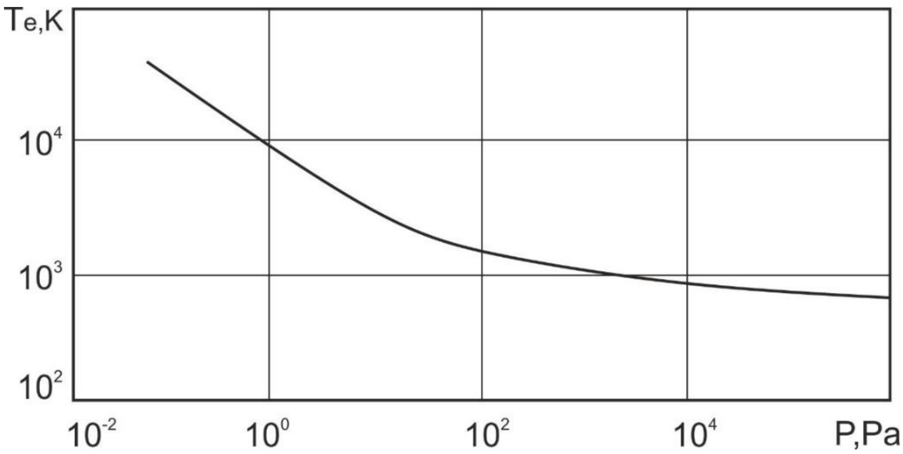


Fig. 4. Dependence of the electron temperature in glow discharge plasma on gas pressure

According to Fig. 4, this range of electron temperatures corresponds precisely to the welding conditions in a glow discharge, which occur within the pressure range of 10^3 – 10^4 Pa. However, from equation (1) it follows that as the electron energy decreases, the power of bremsstrahlung in the visible region of the spectrum also decreases accordingly.

The main process responsible for radiation emission (P_{re}) is volume recombination of ions. Recombination radiation arises when an electron is captured by a positive ion, releasing the energy previously spent on ionizing a neutral atom. The lower the electron energy, and the electron temperature T_e consequently, the more easily the electron can be captured, and the higher the power of this type of radiation [19]:

$$P_{re} = \frac{10^{-21} n_e^2}{(T_e)^{\frac{1}{2}}}, \tag{2}$$

As it was abovementioned, the energy of a free electron may take any value. Therefore, photons emitted during recombination can also form a continuous spectrum. However, the maximum power of recombination radiation is observed at gas pressures above 10^3 Pa when the electron energy drops down below 1 eV. Under these discharge conditions, radiation occurs primarily in the visible region of the spectrum and partially in the infrared.

In [20], it was determined that the total power of bremsstrahlung and recombination radiation at gas pressures of 10^3 – 10^4 Pa reaches 20-25% of the discharge power. Since in diffusion welding processes the discharge power reaches 10 – 30 kW, the corresponding plasma radiation power mainly in the visible spectrum is also significant. This can create serious interference with the use of optical pyrometers based on visual observation for monitoring the thermal state of welded parts.

In some cases, temperature monitoring with optical pyrometers is carried out periodically, by temporarily turning off the glow discharge current during measurement. However, this approach significantly reduces heating efficiency and can only be applied to welded components with high thermal inertia.

Among other technical means of temperature control during diffusion welding in glow discharge plasma, the most effective has proven to be the use of photoelectric pyrometers (PEP). The external view of such a PEP is shown in Fig. 5.

Additionally, to the optical system, a PEP includes a sensitive element a photodiode operating in short-circuit mode, whose spectral sensitivity lies in the wavelength range above 0.7 μm, corresponding to infrared radiation.

Fig. 5. The external view of PEP Flus IR-862

Since the intensity of infrared radiation from glow discharge plasma under diffusion welding conditions is low, this method allows for high-accuracy temperature measurements. Moreover, PEP`s can measure temperature on the surface of a solid body at a point area of 1 mm² from a distance of up to 1 meter, enabling the monitoring of the exact contact zone of welded parts crucial for ensuring weld quality. The PEP`s are located outside the vacuum chamber, which makes them suitable for use in almost all welding setups (see Fig. 6).

The wide range of welded products in diffusion welding determines both a broad variety of materials and diverse geometries of welded assemblies. In some cases, the design of the welded joint may restrict or completely block visual access to the welding zone, making the use of optical temperature measurement methods in this zone impractical or impossible.

In such cases, it is advisable to use indirect temperature control methods by predicting the thermal state of the welding zone or any point within the welded assembly. Such real-time prediction can be performed through mathematical modeling of thermal processes, taking into account the thermophysical and geometrical properties of the materials being welded as well as the energy characteristics of the heating source namely, the glow discharge.

Fig. 6. Diffusion welding setup in a glow discharge equipped with a photoelectric pyrometer PEP-4 [rejuvenated by AI]

Under these conditions, the most effective approach is the use of deterministic dynamic models based on Fourier's heat conduction differential equations with appropriate initial and boundary conditions.

In [21], the main approaches to developing such models were formulated and examples of their practical implementation in glow discharge welding were presented. In particular, the prediction of the thermal state of the welding zone for parts of the simplest geometrical forms (cylinder) made of homogeneous or heterogeneous materials (see Fig. 7).

In [22], results for the development of thermal process models for welding bodies of more complex geometries with extended contact areas are presented. This makes it possible to predict the temperature distribution in the contact zone and adjust it by changing the glow discharge parameters.

The compressive force applied to the workpieces during diffusion welding ensures their plastic deformation in the contact zone, which facilitates the fracturing and fragmentation of the natural oxide films on the contacting surfaces [23]. The magnitude of the compression force should not exceed the yield strength of the more ductile material in the welded pair, in order to limit the degree of deformation. The design of compression systems, and therefore the methods for controlling compression force, do not depend on the energy source used for heating (induction, radiation, or glow discharge) and can thus be considered standardized.

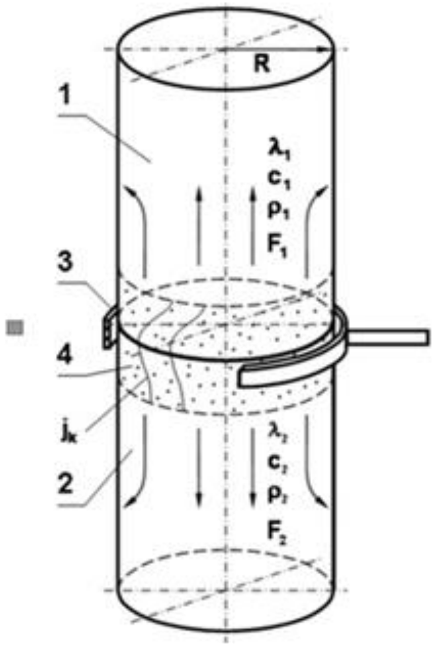


Fig. 7. Scheme of heating by glow discharge:
1, 2 – welded parts; 3 – electrode (anode); 4 – cathode spot of the discharge (heating zone);
j_c – distribution of current density in the cathode spot

An important parameter of diffusion welding is the exposure time of the workpieces under compression at a given temperature. This exposure time is necessary to allow diffusion processes across the contact zone to proceed sufficiently, leading to the formation of common grains, which indicates the elimination of the interface between the two materials and characterizes the quality of the welded joint. Usually, the duration of such isothermal holding is predetermined within a range of several tens of minutes or is determined experimentally.

At the same time, quality control of the joint during diffusion welding can be performed using technical means, particularly by measuring the electrical resistance of the contact zone. The resistance of this zone is higher than that of the base metal due to the presence of defects, such as incomplete bonding areas or oxide inclusions. The value of this resistance depends on the shape, size, and concentration of these defects. The principle of this control method can be based on the dependence between electrical resistance and joint strength as a function of welding time (see Fig. 8).

To minimize the influence of thermoelectromotive force generated in the high-temperature region between the workpiece and the probe contacts, the probes are made of the same material as the parts being joined. After reaching the preset heating temperature and applying the compressive force, a direct current is passed through the workpiece, and its value is monitored with an ammeter. The current strength depends on the size of the parts and the materials being welded, for steels it typically ranges from 1 to 10 A.

When the current passes through the parts and their contact zone, a potential difference arises between the probes, which can be measured using a potentiometer such as the R348 or a similar device. Alternatively, a four-probe micro-ohmmeter (e.g., type M246 or equivalent) may be used. Stabilization of the resistance value at a certain minimum level indicates the completion of strong joint formation.

To measure electrical resistance, it is advisable to use the four-point (Kelvin) method, which eliminates measurement errors caused by instability of the probe–workpiece contact (see Fig. 9).

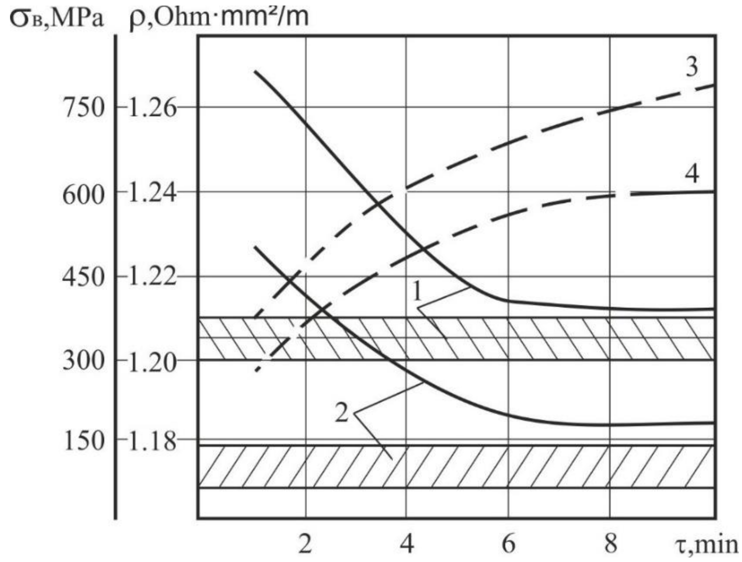


Fig. 8. Kinetics of electrical resistance decrease (1,2) and strength increase (3,4) during the welding of AISI 1045 (1,3) and S235JR (A36) (2, 4). Shaded areas represent the specific electrical resistance of the base metal at a welding temperature of 1273 – 1323 K [24]

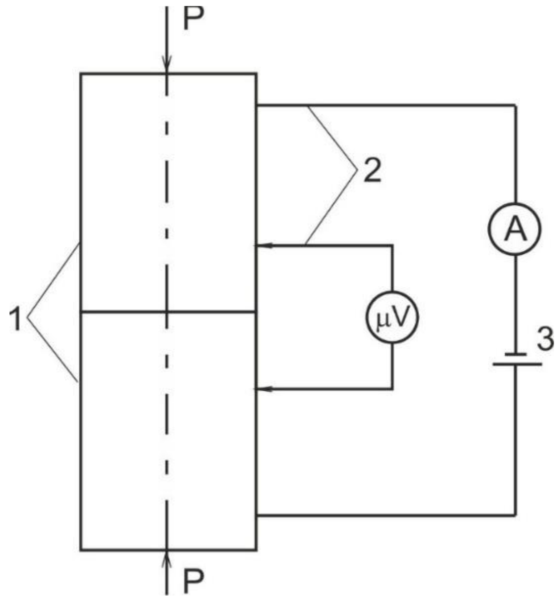


Fig. 9. The Scheme of electrical resistance measurement in the welding zone using the four-probe method:
1–welded parts; 2 – probes; 3 – DC power source

Conclusions. The main technological parameters of diffusion welding in vacuum and the corresponding control methods have been analyzed. It has been established that under glow discharge diffusion welding conditions, the application of traditional thermoelectric and optical methods for monitoring the thermal state of welded parts is limited due to the presence of a strong electric field and plasma radiation on their surfaces.

It was determined that a more effective method for monitoring the temperature in the welding zone under such conditions is the use of photoelectric pyrometers, whose spectral sensitivity corresponds to the infrared range of electromagnetic radiation emitted by the heated workpiece.

An efficient and promising approach for monitoring the temperature in the joint zone when welding parts of various shapes and sizes made from dissimilar materials is the use of computational prediction methods. These are based on deterministic mathematical models that allow real-time forecasting of the temperature evolution in the welding zone.

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КОНТРОЛЬ ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ТА ЯКОСТІ ДИФУЗІЙНОГО ЗВАРЮВАННЯ В ПЛАЗМІ ТЛІЮЧОГО РОЗРЯДУ

Для отримання зварних з'єднань з однорідних та різнорідних матеріалів у виробах нової техніки широко застосовують дифузійне зварювання, яке здійснюється у твердому стані у вакуумі. Основними параметрами цього способу є температура нагріву зварюваних деталей, зусилля їх стискання та тривалість ізотермічної витримки або зварювання.

Дифузійне зварювання відноситься до низькосилових способів зварювання. Відносно невисокі температура та обмежене зусилля стискання дозволяють отримувати прецизійні зварні з'єднання, що не потребують подальшої механічної обробки. Головним параметром дифузійного зварювання є температура нагріву зони контакту з'єднуваних деталей. Експериментально визначено, що залежність міцності з'єднання від температури має екстремальний характер, тобто максимальна міцність досягається у вузькому діапазоні температур. Тому контролю температурного стану зони зварювання приділяється особлива увага.

У процесах дифузійного зварювання з індукційним та радіаційним нагрівом, що здійснюються у вакуумі, контроль температури здійснюється термопарами або оптичними пірометрами. Для процесів зварювання у плазмі тліючого розряду застосування цих методів обмежено. Це обумовлено, в першу чергу, наявністю світіння плазми на поверхні деталей. Аналіз фізичних особливостей розрядної плазми в умовах дифузійного зварювання при тисках газу 103…104 Па показує, що максимальна інтенсивність випромінювання плазми припадає на видиму область спектра електромагнітних хвиль, що не дозволяє застосовувати оптичні методи контролю. Найбільш ефективним методом у такому випадку є застосування фотоелектричних пірометрів, спектральна чутливість яких знаходиться у межах інфрачервоному випромінюванню зварюваних деталей.

При зварюванні деталей складної форми, коли візуальний контроль зони зварювання може бути обмеженим або недоступним, ефективним методом є прогнозування у реальному часі температурного стану зони з'єднання або будь-якої точки в об'ємі заготовок на основі математичних моделей процесу нагріву. Час зварювання визначає ступінь завершення дифузійних процесів, тобто момент зникнення зони розділу між деталями і, відповідно, якість зварювання. Зазвичай, оптимальний час зварювання знаходиться експериментально. Однак, необхідна тривалість ізотермічної витримки може бути визначена безпосередньо в процесі зварювання технічними засобами, зокрема неперервним вимірюванням електричного опору зони зварювання чотирьохзондовим методом (методом Кельвіна). Зниження опору в процесі зварювання та його стабілізація на мінімальному рівні свідчить про утворення міцного з'єднання.

Ключові слова: *дифузійне зварювання, тліючий розряд, плазма, технологічні параметри, контроль якості.*

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