COMBINED FUSION WELDING TECHNOLOGIES (Review)

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Combined and hybrid welding technologies by using gas flame, electric arc, laser and electron beam as heat sources, as well as different shielding methods, are analysed. The expediency of commercial application of different methods for two- and three-arc welding with 1–2 mm diameter consumable electrodes is shown. It is suggested using the arc and gas flame, laser and electron beam as the combined heat sources.

Keywords: *combined and hybrid technologies, energy sources, electric arc, gas flame, laser, electron beam, shielding atmosphere*

Solving the problems of weldability of a specific material and assurance of the required quality of the welds and joints on welded structures at a sufficient productivity is the main task of the welding technology [1–4]. With different fusion welding technologies, this task is handled by choosing a type, power and distribution of heat sources between consumers, combining electrode and filler materials in terms of their shape and chemical composition, kind and composition of shielding of the welding zone, as well as other methods and approaches [1, 2, 5, 6]. In particular, in welding production the acceptance has been gained by the combined technological processes, which use simultaneously two or more similar or dissimilar energy sources [7, 8]. In case of utilisation of the dissimilar energy sources affecting one treatment zone (e.g. the weld pool), where the integrated result exceeds the sum of the results of each constituent energy source, the process is called the hybrid one. The growth of interest in the hybrid welding processes, where the use is made of the combined energy of the laser beam, plasma and electric arc, has been noted in the last years [9].

The purpose of this study is to analyse the existing fusion welding technologies and define the new possible areas of upgrading these technologies based on combining the energy input into the work zone and its shielding atmosphere.

Combining the energy sources and shielding atmospheres. In welding, the main energy sources are chemical reactions occurring with release of heat (exothermic), electric arc, low-temperature plasma, electron beam, laser radiation, resistance, electroslag and induction heating, heating in electrolytes, friction and ultrasonic heating [1, 3, 5, 6, 10, 11]. If necessary, the mechanical energy is fed to the welding zone by static, dynamic or pulse loading.

Table 1 gives the existing and possible combinations of welding methods based on the combinations of energy sources and kinds of mechanical loading for joining metallic materials.

Naturally, the quantity of the possible welding methods can be increased due to triple combinations of thermal energy sources and kinds of mechanical loading.

Different methods for metal shielding from air can be used within a specific fusion welding process (Table 2) [9, 12].

In case of using several heat sources, both identical shielding methods and methods differing in shielding composition and design can be used for each of the sources.

While performing its main function of shielding the molten metal from air, the shielding atmospheres exert a huge effect on physical, metallurgical and technological characteristics of the welding process.

Some known welding methods and methods suggested by the author, involving a combination of heat sources and shielding atmospheres, are considered below.

Consumable-electrode two- and three-arc welding. Mechanised consumable-electrode arc welding takes the leading position among other welding technologies. Single-arc welding has the widest application. Less widespread are two-, three-, four- and five-arc welding in the common pool [9]. The last two technologies are used mainly for manufacture of large-diameter pipes. Submerged two- and three-arc welding with 3–5 mm diameter wires is employed in ship and tank building, pipe production, for manufacture of different-purpose beam and sheet structures with extended welds.

As shown in study [13], two- and three-arc welding in shielding gases and by the submerged

Table 1. Combining of sources of thermal energy and kinds of mechanical loading in welding

Source of thermal energy and kind of mechanical loading	GF	TR	EA	LTP	EB	LB	RH	ESH	HE	IH	F	US	SL	DL	PL
Gas flame (GF)	+	+	+				+	+		+	+		+	+	
Thermit reaction (TR)	+	+	+					+		+		+	+	+	
Electric arc (EA)	+	+	+	+		+	+	+		+		+	+	+	
Low-temperature plasma (LTP)			+	+		+			+	+			+	+	
Electron beam (EB)			+		+	+				+		+	+	+	
Laser beam (LB)			+	+	+	+	+		+	+		+	+	+	
Resistance heating (RH)			+			+	+		+	+	+		+	+	+
Electroslag heating (ESH)		+	+	+				+		+		+	+		+
Heating in electrolytes (HE)				+		+	+			+		+	+	+	
Induction heating (IH)	+	+	+	+	+	+	+	+		+	+		+	+	
Friction (F)	+						+			+	+		+	+	
Ultrasound (US)			+	+	+	+		+	+	+	+		+	+	
Static loading (SL)	+		+		+	+	+	+	+	+	+	+	+	+	
Dynamic loading (DL)	+	+	+	+	+	+	+		+	+	+	+	+	+	
Pulse loading (PL)							+	+							+

Note. The «+» sign means that the process is applied or is possible.

arc method using 1–2 mm diameter electrode wires, considering their technological capabilities, is reasonable to apply more extensively instead of single-arc welding using 3–5 mm diameter wires, including for addressing such important problems as rise in labour productivity (2–3 times), decrease in heat input (1.7–2 times), reduction of residual strains, and providing of the required service characteristics of different metal structures.

Increased spattering and violation of stability of the process as a result of magnetic interaction of the arcs are considered to be the key drawbacks of gas-shielded two- and three-arc welding. At the same time, these and other problems can be successfully solved with the help of the existing

Table 2. Types of shielding of molten metal from air with different fusion welding methods

Shielding method	Welding method					
	Gas	Arc	Plasma	Laser	Electron beam	Electroslag
Gases:						–
inert	–	+	+	+	+	–
active	+	+	+	+	–	–
mixtures	+	+	+	+	–	–
vapours	–	+	–	–	–	–
continuous jet	+	+	+	+	+	–
annular jet	–	+	–	+	–	–
two-layer jets	–	+	+	+	–	–
two-velocity jets	–	+	+	–	–	–
pulsed jet	–	+	+	+	–	–
in chambers	–	+	+	+	–	–
Gases and slags	+	+	+	+	+	–
Slags (submerged arc)	–	+	–	–	–	+
Creation of vacuum	–	+	+	+	+	–

Note. The «+» sign means the possibility of using a shielding method, and the «–» sign — a shielding method is not used.

capabilities of electrical engineering, electronics and welding metallurgy (rational powering of the arcs, special current sources, control systems, shielding gas atmospheres, flux-cored wires, etc.).

One of the lines of further upgrading of two-arc welding with the open arcs can be the use of two-velocity gas shielding of one (first) or both arcs (Figure 1).

In the first variant shown in Figure 1, *a*, arc *1*, which is the first in the course of welding and powered by the direct current of reverse polarity, is additionally constricted by the shielding gas flow fed via nozzle *2* at a velocity that is much higher than that of the main shielding gas flow fed via nozzle *3*. The main shielding gas is used to shield molten metal and second arc *4*.

In the second variant (Figure 1, *b*), the high-velocity flow is also used for constriction of second arc *4*. In this case the concentration of heating is higher than in the previous case. The efficiency of using the additional high-velocity flow of argon gas was first investigated in consumable-electrode single-arc welding of aluminium [13, 14]. In this case the penetration depth and full thermal efficiency of the welding process under optimal conditions were increased approximately 2 times. In fact, this is consumable-electrode plasma-arc welding, and improvement of energy characteristics is related to the additional constriction of the arc and improvement of heat transfer to the base metal under the effect of the high-velocity gas flow.

It is shown in study [15] that raising the velocity of the additional flow of shielding gas to 40 m/s allows increasing the depth of penetration of steel 1.5–2 times, compared to the penetration depth achieved with the traditional welding method using 1.0–1.2 mm diameter electrode wire. In welding at a high velocity of the additional CO_2 jet, the resulting weld is narrow and characterised by a penetration coefficient of 0.71–0.33, as well as by a high reinforcement without smooth transition to the base metal.

In our opinion, formation of the welds can be improved due to using two arcs burning into one common pool and powered from separate sources.

In this case, both similar and dissimilar gases (gas mixtures) can be used for additional constriction of the arc (arcs) and shielding of the welding zone. Improvement of the weld formation and decrease of spattering can also be provided due to heteropolar burning of the first and second arcs (variant V_2), powering of the second arc by the alternating current (variant V_3) (see Figure 1, *a*) and using one or two flux-cored wires.

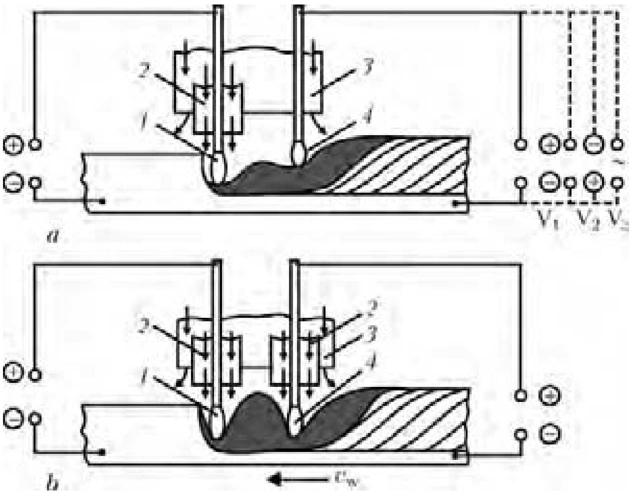

Figure 1. Schematic of two-arc welding with two-velocity gas shielding of one (*a*) and two (*b*) arcs: *1*, *4* — the first and second arc, respectively; *2* — nozzle for feeding the high-velocity gas flow; *3* — nozzle for feeding the shielding gas at normal velocity

The effect similar to the use of flux-cored wire can also be achieved by feeding a small amount of flux of a corresponding composition to the welding zone, including with the high-velocity gas jet. This process can be applied for welding of steels and other alloys, and aluminium alloys in particular.

Gas-shielded three-arc welding with 1–2 mm diameter consumable electrodes into the common pool is insufficiently studied so far. In case of three-arc welding, of high importance is the power circuit of the arcs that minimises their magnetic interaction. Three possible variants of connecting the arcs to independent current sources are shown in Figure 2. According to the variant shown in Figure 2, *a*, the first and third arcs in the course of welding are powered by the direct current of reverse polarity, while the second arc is powered by the direct current of straight polarity. As the direction of the current flowing through the first and third arcs does not coincide with that of the current flowing through the second arc, they will be repelled from it, and the welding process will be more stable than in powering of all the three arcs by the reverse polarity current.

With the arc connection variant shown in Figure 2, *b*, the first arc is powered by the direct current of reverse polarity, the third arc — by the direct current of straight polarity, and the second arc — by the alternating current. In this case the first and third arcs alternately, at a frequency of the alternating current, are attracted and repelled with respect to the second arc.

The arc powering variant shown in Figure 2, *c*, can have some advantages in welding of fer-

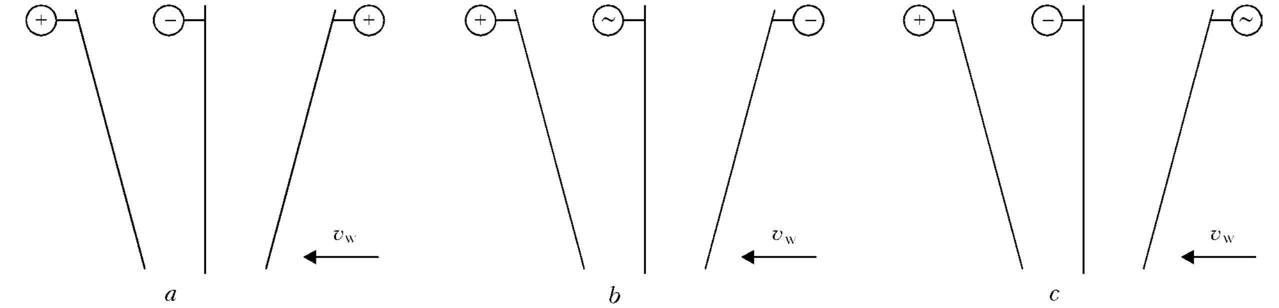

Figure 2. Schematics of electrode connections in gas-shielded three-arc welding at direct current (*a*) and at direct and alternating currents (*b*, *c*)

romagnetic materials, compared to the variant shown in Figure 2, *b*.

Increase of the process stability with all the variants considered can be achieved due to optimisation of the welding parameters, selection of a corresponding shielding gas (gas mixture) and using of two or three flux-cored electrode wires. In the case shown in Figure 2, *a*, the rational combination can be the one where a non-consumable tungsten electrode is connected to the DC source or powered by the modulated current.

Three-arc welding can provide an approximately three times increase in productivity and substantially widen the range of adjustment of heat input when joining different materials. In welding practice, often it is necessary to have a finer adjustment of heat input and local redistribution of heat within the forming weld pool. For this purpose, powering by the modulated current or oscillations of the electrode tip following different paths are used in gas-shielded and submerged single-arc welding [9].

Two- and multi-arc welding opens up extra possibilities for achieving the effect of current modulation and electrode oscillation. As an example, consider the welding method shown in Figure 3. Here it is suggested using two arcs, which differ substantially in their power, namely: power of the second arc in the course of welding is much lower than that of the first arc. In this case the basic characteristics of the process (heat input, productivity) are determined mainly by the power of the first arc, whereas the second arc having a relatively lower power serves for fine adjustment of thermal, hydrodynamic and metallurgical processes occurring in the weld pool. This effect of the second arc is increased due to the use of mechanical oscillations of the second electrode (Figure 4) or modulation of the current this arc is powered by.

The choice of this or that kind of oscillations and its parameters depends on the desired tech-

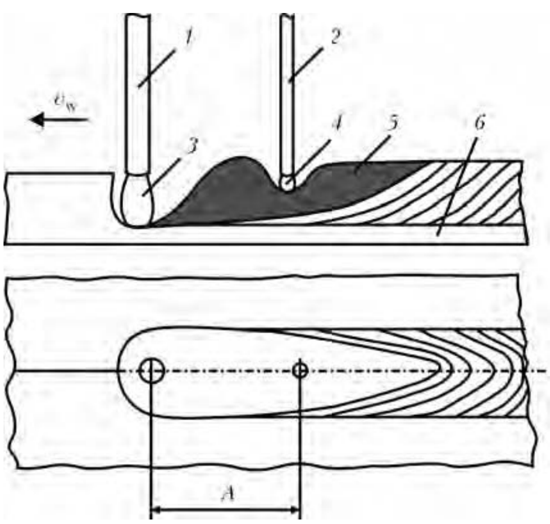

Figure 3. Schematic of two-arc welding method with two arcs having asymmetric power: *1*, *2* — first and second electrode, respectively; *3*, *4* — first and second arc, respectively; *5* — weld pool; *6* — workpiece; *A* — distance between electrodes

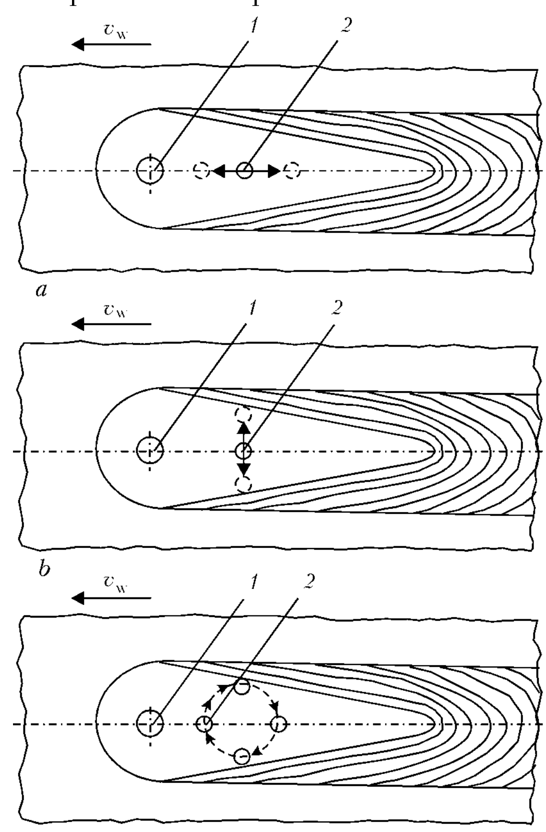

Figure 4. Schematic of two-arc welding with oscillations of the second electrode along (*a*) and across the weld (*b*) and on the circumference (*c*)

nological effect (improvement of the weld formation, increase of the welding speed, decrease of the content of harmful gases in the weld pool, increase of crack or porosity resistance, decrease in the amount of non-metallic inclusions, improvement of mechanical properties and service characteristics of the welded joints).

The variant of the two-arc process with the second arc powered by the modulated current, where the first arc is stationary, makes it possible, with no changes in basic parameters of the first arc and, hence, main conditions of formation of the weld (in particular, the penetration depth), to actively affect its solidification due to feeding the current pulses to the second arc located in the tailing, colder part of the weld pool. This creates more favourable conditions and widens the possibilities for adjustment of the weld formation and solidification process, compared to single-arc welding at the modulated current.

Implementation of the suggested method is possible also in a variant of the combined use of oscillations of the second, low-power arc and its powering by the modulated current. In this case the current pulses can be fed both constantly along the entire path of movement of the arc and at its separate points, including by using instantaneous stops of the electrode at these points. The latter case offers additional possibilities for thermal cycling treatment of different zones of a welded joint depending on the type and composition of the materials welded.

The said method can be implemented both in submerged arc and gas-shielded welding of different-application materials not only without any decrease in productivity, but with its 1.3–1.5 times increase.

Hybrid welding (arc + gas flame). Reaction of combustion of hydrocarbons is widely used for generation of heat in welding and related processes.

The low heat values in combustion of main fuel gases and temperatures of the flame in a mixture with oxygen are given in Table 3 [16]. The effective thermal power of the flame is adjustable over very wide ranges.

Table 3. Low heat value in combustion and temperature of flame of fuel gases in a mixture with oxygen

Gas	Low heat value in combustion, mJ/m^3	Temperature of flame in mixture with oxygen, °C
Acetylene	100.8	3100–3200
N-butane	111.2	2700–2900
Hydrogen	19.2	2400–2600
Methane	32.0	2400–2700
Propane	83.2	2700–2850
MAPP gas	83.2	2800–2900

In standard flame equipment (welding and linear hardening torches and oxygen cutters) the velocity of outflow of the mixture is within 40–160 m/s, in rocket type units it is 800–1000 m/s, and in detonation spraying units — up to 3000 m/s [16, 17].

The maximal pressure of the gas jet to the weld pool at velocities of outflow of the fuel mixture 120–150 m/s can amount to 1 Pa, while the penetration depth at a high thermal power of the flame is 15 mm [17]. The pressure of the arc flow is known to be proportional to the square of the current intensity. In TIG welding in argon atmosphere at a current of 200 A the pressure on the arc flow axes is $5\cdot10^{-2}$ Pa [5]. As the current is increased to 500 A, the pressure grows approximately 2 times, remaining by an order of magnitude lower than in the above case of gas welding.

Although the gas flame is a less concentrated heat source (10^2–10^3 W/cm^2) than the electric arc (10^3–10^5 W/cm^2), it is characterised by a number of advantages:

- possibility of a very flexible adjustment of distribution of heat over the set surfaces of a workpiece, as well as between the base and filler metals in welding and surfacing;
- it is insensible to the effect of magnetic fields;
- gas dynamic effect on the molten metal surface can be varied over wide ranges and used for adjustment of the penetration depth, weld formation and holding of molten metal in the weld pool, including at different spatial positions of the weld.

As early as 1930, H. Muenter introduced the «arcogen» welding method, which combined heating by the acetylene-oxygen flame and by the electric arc. Because of complexity of the manual welding techniques available at that time, this method could not compete with the existing simpler methods using one heat source [18].

We can cite just one known example of commercial application of the combined electric arc and gas flame welding technology — it is arc welding with preliminary or concurrent heating by the gas flame. In this case the gas flame heat source acts outside the weld pool, whereas the hybrid welding method provides for the use of two dissimilar heat sources (in this case the arc and gas flame) affecting one treatment zone (weld pool). This effect can be realised by different ways (Figure 5).

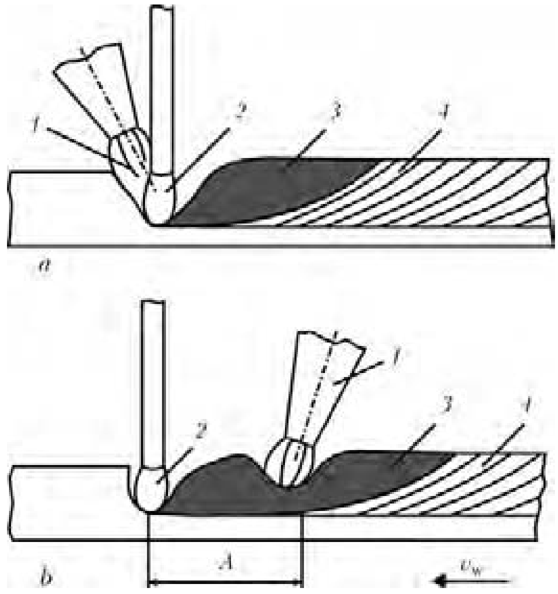

Figure 5. Schematic of hybrid arc + gas flame welding: *a* — gas flame is ahead of the arc; *b* — behind the arc; *1* — gas flame; *2* — electric arc; *3* — weld pool; *4* — weld

Figure 5, *a* shows a variant of hybrid welding using the electric arc and gas flame. Here the gas flame is located ahead of the electric arc in the immediate proximity to it. In this case the gas flame can promote increase in the penetration depth and electrode wire melting rate, as well as affect transfer of the molten metal through the arc gap.

In a variant of hybrid electric arc + gas flame welding shown in Figure 5, *b*, the gas flame heat source is located behind the arc, and by changing distance *A* between the heat sources it is possible to widely change the thermal cycle of welding and weld formation, including in making the multilayer and fillet welds.

Hybrid electric arc + gas flame welding can be implemented in a combination with gas and gas-slag shielding in a variant of the mechanised process. Considering specifics of the offered technology, it can be used for welding and repair of parts made from carbon steels, cast iron, copper and copper alloys.

Combined technologies of laser, electron beam and arc welding. In the last years more interest has been shown in laser welding, hybrid and combined welding methods [19].

Various approaches and methods, including the combination of laser heating with plasma arc or high-frequency one, are applied to increase the economic efficiency of laser welding (decrease in requirements to edge preparation, reduction of the risk of formation of thinning, porosity and undercuts, decrease in capital and other expenditures) [9, 11, 20–25].

It was established [20] that in one-pass hybrid welding of more than 5 mm thick steels the 1 kW power of the arc can be replaced by the 0.5 kW power of laser radiation. The case in point is using lower-power (less expensive) lasers for welding thick metal, which is economically attractive in a number of cases. However, it was found out that the use of the hybrid process at a fixed power of laser radiation makes sense only up to a certain thickness of the metal welded, above which the penetration depth does not grow independently of decrease in the welding speed. For further intensification of the penetration process it is necessary to increase the power of laser radiation.

It is considered [19] that capital expenditures for a fibre laser unit are about 0.1 Million Euro per 1 kW of the output power. Therefore, the economic efficiency of laser-arc welding will be determined primarily by the capital expenditures for purchase of a higher-power laser unit.

If we proceed from the requirement to increase the penetration depth in laser welding without increase in power of the laser unit, then this problem can also be solved by using vacuum shielding. On the one hand, this deprives the laser beam of certain advantages over the electron beam and, on the other hand, even a small degree of evacuation allows increasing the penetration depth from 3 to 5 times [26]. Moreover, specifics of the laser beam make it possible to transfer it through a transparent barrier or by using fibre optics, which can be utilised for manufacture of a number of parts in a vacuum chamber.

In laser welding in vacuum by using the about 5 kW beam, it is likely that the penetration depth on steel can be increased to 20 mm. This penetration in a case of conventional laser welding can be achieved at a laser power of about 20 kW, i.e. implementation of this technology will additionally require about 1.5 Million Euro of capital expenditures.

In vacuum laser welding, the additional capital expenditures will be required for a vacuum chamber and evacuation system. If these expenditures do not exceed 1.0–1.3 Million Euro, the variant of vacuum laser welding of 20 mm thick metals is economically justifiable.

The problem of vacuum laser welding can have a simpler solution, if a company already has an active electron beam welding unit. The vacuum system of this unit can be used for laser welding. Moreover, in this case the economic prerequisites are created for implementation of hybrid laser beam + electron beam welding. The technological effect and economical expediency of this process are hard to estimate today. The electron beam and laser have a different nature, but their combination is quire acceptable, given that the laser beam is insensitive to the effect of magnetic fields and can be used with the electron beam in different variants. Experiments are required. As to combined electron beam and arc welding, such experiments were conducted [27].

It was established that in two-sided combined welding the arc discharge widens the keyhole in the root part of the weld. The forces caused by the effect of the electron beam and arc discharge on the molten metal have opposite directions, this resulting in stabilisation of hydrodynamic processes in the penetration channel, decrease in spattering and increase in resistance of the molten metal to flowing out over a wide range of the process parameters.

CONCLUSIONS

1. Two- and three-arc welding with 1–2 mm diameter consumable electrodes, using gas and gas-slag shielding of molten metal, additional constriction of the arc (arcs) by the gas flow, powering of one of the arcs by the modulated current, and displacement of the electrode tip along the preset paths, allows increasing the productivity, reducing the heat input, redistributing the heat flows in the weld pool, and improving the weld formation. These technologies are indicated for fabrication of metal structures of carbon, low-alloy and stainless steels and aluminium alloys, the weldability of which is insufficient for using traditional single-arc welding.

2. The conducted analysis showed a high potential of using in welding processes the combinations of such energy sources as the electric arc and gas flame, as well as the laser and electron beams, as these combinations allow increasing the penetration depth and improving the weld formation with simultaneous reduction of cost of the welding process (compared to achieving penetrations of the same depth by using one of the above sources).

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