γ-TiAl were derived. Accuracy of digital videonavigation and precise application of the indenter allowed revealing and getting imprints of structural microinhomogeneities in the form of individual intermetallic precipitates in the interlayer, as well as zones with different microhardness values. The undesirable change of microhardness should be regarded and taken into account simultaneously with the changes of Young modulus of elasticity and coefficient of ductility.

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FROM HISTORY OF WELDING

TRENDS IN DEVELOPMENT OF COMBINED AND HYBRID WELDING AND CLADDING TECHNOLOGIES

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The history of development of the technologies based on the interrelated simultaneous action of two heat energy sources is considered. It is suggested that the combined and hybrid processes should be discriminated. The combined processes involve the action of several sources, which are either identical or of the same type, whereas with the hybrid processes the use is made of the sources differing in their physical characteristics, which impart new technological properties to a process.

Keywords: *fusion welding, cladding, arc welding, plasma welding, laser welding, combined welding, hybrid welding, history of technology*

Every welding method has certain advantages and disadvantages. Development of the combined and hybrid technologies involves integration of technological and other advantages of individual welding methods and minimisation of their drawbacks. Main challenges facing the welding industry include increase of the welding speed, decrease of the metal and power consumption, control of the weld shape, and improvement of the quality of welded joints. The problem of widening the range of thicknesses of pieces joined has been successfully tackled in the field of fusion welding for many years, while in the field of cladding such a problem consists in minimisation of penetration and decrease of the fusion zone between a workpiece and deposited layer (bead). These problems can be efficiently solved by distributing heat input, heating and melting between the two (or more) energy sources, which simultaneously act in the common welding/cladding zone. In this case, each of the sources can perform insignificantly or substantially different functions. It should be noted that such methods are sometimes termed «combined» or «hybrid» in corresponding publications, assuming that the new technological effect is a generalising attribute of these terms. To tell the difference, it is necessary to consider the history of development of the welding and cladding technologies using several energy sources.

According to study [1], the hybrid welding processes are a combination of two (or more) conventional (standard) processes, resulting in the effects which cannot be achieved by each of the processes taken separately. R.V. Messler dates emergence of the first hybrid technology back to 1972. He starts from the method developed by W.G. Essers and A.S. Lifken at a «Philips» (The Netherlands) laboratory [2]. In Ukraine the «plasma-MIG» term is already approved in the State Standard for terminology for this type of welding (cladding) [3].

Definition «hybrid welding» has not been officially approved as yet. Notion «hybrid» (from Latin «Hibreda» — mixture) belonged, starting from the 18th century, to biology, i.e. cross breeding of animals or types of plants [4]. The combined or integrated processes, units, systems and devices with different properties and characteristics, resulting in achievement of a new technical effect (e.g. hybrid computer

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systems, integrated circuits, interconnections of radio duct systems) were started to be referred to as the hybrid ones in the 20th century. R.V. Messler considers the action on a common weld pool by two laser beams going in series along the axis of a joint or on each side of the axis also to be among the hybrid welding processes. He thinks that this qualification of the «hybrid process» is grounded on the effect of improvement of weld formation, rather than on differences in technical characteristics of components. The definition he suggested is not clear enough, as in this case the submerged two- and three-arc welding methods should also be classed with the hybrid ones, as they make it possible to solve the problem of weld formation at a speed increased dozens of times and, thus, put off the date of emergence of the hybrid technologies by twenty years [5].

In multi-arc welding developed by the E.O. Paton Electric Welding Institute, each of the heat sources arranged in series performs a certain function: the first prepares (penetrates) the edges, the second fills up the gap between the edges (pool), and the third finally forms the weld [6].

Technologies for submerged-arc welding by using five electrodes simultaneously were developed abroad in the 1980s. Multi-electrode systems with parallel electrodes, i.e. direct current–direct current, direct current–alternating current and alternating current–alternating current systems, and a system of three AC sources, found the widest commercial application [7]. However, these technologies cannot be called the hybrid ones — they are the combined processes using similar sources.

The first process called the hybrid one was welding with the laser beam plus arc (arc plasma) [8]. For some time only this process was considered to be the hybrid one, until R.V. Messler classed the plasma-MIG process also with the hybrid processes [1]. Both processes have similar flow diagrams, i.e. with plasma-MIG there is another heat source, i.e. the metal-electrode arc, inside the circular arc (plasma). Moreover, these sources differ in physical and technological properties [9].

It should be noted that emergence of the plasma-MIG method was preceded by the development of other welding methods using two dissimilar heat sources.

The purpose of this study is to refine classification and range of the combined and hybrid processes allowing for the chronology of their development. Here the physical essence of energy sources (similar or dissimilar in their nature), their impact on a workpiece and interaction between them, resulting in formation of a new effect, should be used as a basis, like in the already standardised terminology [3]. It is suggested that welding and cladding processes based on interaction of the energy sources that are similar in their physical nature and technological properties should be considered the combined processes. The hybrid processes are an integration of two (or more) dissimilar (in terms of physical phenomena) heat sources, resulting in formation of a new technological effect.

The retrospective analysis shows that both types of the processes emerged almost at the same time. At the end of the 1880s N.N. Benardos introduced the combined two-arc welding technology. The point of the first hybrid technology was that a gas flame was burning around the carbon-electrode arc [10]. N.N. Benardos designed a special torch for this technology. A combination of the heating flame and melting action of the arc widened technological capabilities of the process both for welding and cladding. In the same years E. Thomson employed a concurrent spark and arc heating to increase the productivity of resistance butt welding [11].

Another method put forward by N.N. Benardos, i.e. welding, soldering and cladding with the arcs burning simultaneously from the consumable and non-consumable electrodes, also solves the problem of preheating, like its arc-gas process. However, it cannot be defined as the hybrid one. In 1930 H. Munter developed a method incorporating acetylene-oxygen welding and metal-arc welding, the so-called «arcogen» method. With this method the gas flame provided about 60 % of heat, and the AC arc — 40 %. The amperage was 2–3 times lower than in open-arc welding, thickness of metal welded being the same. However, voltage in this case amounted to 100 V. This is attributable to the fact that the flow of gases caused intensive ionisation of the arc column. The procedure of such a welding was complicated, as a welder had to perform both processes manually. This method could not compete with the simpler methods involving one heat source, which were widely applied at that time [12].

V.P. Nikitin was a supporter of the hybrid processes. He noted: «Fusion welding in the course of its development until the last years has been characterised by the permanent fundamental principle: one heat source is used for two different thermal operations (fusion of the base metal and melting of the filler metal). Strong, hardly controllable relationship between thermal preparation of the base and filler metals leads in many cases to reduction of the productivity and deterioration of the welding quality, thus limiting its application. With single-arc welding the basis for rise in the productivity is increase in the arc power. The productivity of welding with a high-power arc is determined, primarily, by the efficiency of penetration of the base metal, as the electrode metal constitutes 20–25 % of the weld. Deep penetration hampers achievement of the satisfactory quality of welding of steel to copper, brass, bronze and other alloys. Moreover, in some cases this leads to decrease in anticorrosion and antifrictional properties of alloys. The above limitation is equally applicable to cladding of high-speed steel and hard alloys on carbon steel at a high power of the arc and strong relationship between thermal preparation of the base and filler metals. Concentration of the alloying elements that determine properties of the deposited layer decreases because of dilution with the base metal: composition of the weld metal in such cases differs from the preset one, and it is difficult to regulate it. All modern melting methods characterised by the strong relationship are totally irrational for application to cladding operations. So, the welding methods should be developed with allowance for their energy basis» [13, p. 234]. In 1941, V.P. Nikitin suggested a method providing for a separate control of heat input, i.e. an integration of the arc heating and melting by feeding a metal preliminarily melted (and overheated) in the furnace from a separate crucible to the welding zone. The low-current arc discharge in this hybrid process was required for surface preparation (cathodic cleaning and incipient melting), thus providing a high quality of cladding. Despite a high productivity of the device incorporating the arc torch and electric crucible, it found a limited application because of its complexity [14].

The method of gas-shielded fusion arc welding by feeding a filler metal to edges of the parts joined via a hollow electrode aligned with the arc to the arc zone is characterised by the fact that, to increase the productivity of the process and widen the range of thicknesses of the parts welded, the filler metal is fed via the hollow electrode to the arc zone in a molten state, melting of the filler metal being provided by its passing through a high-frequency inductor [15]. The E.O. Paton Electric Welding Institute returned back to the idea of a separate formation of the pool (penetration and filling) at the beginning of the 1960s, when developing technologies for plasma-arc welding. Through penetration was considered to be the main technological feature of the process. The weld pool with a hole (the process was termed «the keyhole» — effect) allowed the plasma-gas flow to go out from below of a welded joint [16]. However, intensification of the plasma-gas pressure to increase the welding speed and penetration depth leads to deterioration of the weld formation, formation of undercuts and even cuts. To achieve a satisfactory weld formation, the E.O. Paton Electric Welding Institute suggested filling the weld pool with a filler metal melted in a high-frequency inductor. Thus the welding speed was increased 4–5 times. The plasmatron and inductor were assembled in one welding head on a carriage. Nevertheless, it was difficult to control such a process because of substantial differences in principles of operation of the equipment.

To solve this problem in high-speed plasma welding, it was suggested at the end of the 1960s that the pool should be filled up with the electrode metal melted by the pulsed metal-electrode arc. In this case the arc crosses the plasma-gas flow. Part of the wire electrode at a short arc receives extra heat [17]. At the end of the 1960s, it was necessary to use two different current sources with a single control device to implement this method. Circuit of the control device was based on the electromagnetic relay, and was complicated and sluggish. Welding by using the plasmatron with a zirconium electrode pressed into a copper holder allowed using the carbon dioxide gas as a plasma gas, thus making it possible to joint steel plates of a comparatively big thickness in one pass. This process (which can be classed with the hybrid ones) turned out to be stable at a metal electrode current of only 20–40 A. The penetration depth in this case was less than 1 mm [18]. The Paton Institute returned back to improvement of this process and development of the specific technologies based on the combined action of metal- and tungsten-electrode constricted arcs in the 1990s [19]. Investigations of the process combining the tungsten electrode arc with the arc of a metal electrode fed to the same weld pool were conducted on samples of aluminium alloys 8 mm thick. The search for rational flow diagrams of metal- and tungsten-electrode welding processes, and spot plasma-arc welding, went on in the years that followed, and efforts were made to develop the equipment for implementation of these processes.

Among all TIG welding processes it is the tungsten-electrode helium-arc welding (HAW) method that features the highest penetrating capacity. The welding technology combing different heat sources, i.e. HAW and metal-electrode argon-arc welding, was developed to solve the problem of the satisfactory weld formation in making of long welds with a variable gap [20]. The process parameters can be rapidly and flexibly adjusted in automatic through-penetration butt welding without backing, thus providing a good quality of the weld metal and minimal weakening of aluminium alloys.

By the beginning of the 21st century the combined methods, featuring the use of two successively arranged electrode wires (tandem welding) and a strip electrode, as well as the spray or rotating arc, performed preferably under the pulsed welding conditions, were considered to be the most efficient versions of MAG welding [21].

The technologies based on the plasma-MIG process (known abroad as a «Philips-process») were applied to manufacture unique structures, including nuclear reactors [22]. At the end of the 1990s the plasma-MIG welding and cladding processes were studied at the E.O. Paton Electric Welding Institute and Priazovsky State Technical University. It was established that the current is flowing not only through the electrode wire, but also through the hollow-cylindrical arc plasma surrounding the wire. Separate heating of the surface and melting of the electrode showed good results in flux-cored wire cladding [23–25]. The presence of the plasma surrounding the metal electrode and arc provides a much wider range of currents in the electrode wire, within which the arcing process is stable, the efficiency of melting grows, and the critical current of transition to spray and spray-rotating transfer of the electrode metal decreases [26].

The technology for welding stainless steels, featuring the integrated use of the plasma arc and tungsten-electrode arc, thus providing the quality welds at an increased welding speed, was developed in France [27]. A similar hybrid scheme of integration of the plasma-arc and metal-electrode arc processes in one torch was applied at the E.O. Paton Electric Welding Institute for spot welding [28].

Two-sided welding with opposite heat sources, i.e. the plasma (constricted) arc and metal-electrode arc, plasma arcs, etc., can be qualified as a hybrid process. This type of welding was first put forward by the E.O. Paton Electric Welding Institute in 1966 for welding vertical welds [29], and covered by the State Standard of Ukraine under the term of «bipolar arc welding» [3]. The Department of Metallurgy and Materials of the College of Science and Technology (London, Great Britain) developed the technology for welding with the laser and arc arranged according to the same scheme [30]. Another technology for TIG welding of high-strength aluminium alloys in argon atmosphere by using two oppositely directed torches was developed in the USA [31]. At the end of the 20th century the laser-arc welding and cutting methods were started to be called the hybrid methods. V.Yu. Khaskin notes: «Discrimination is usually made between the hybrid and combined processes. The first provides for feed of the focused laser beam and electric arc to one point in the common pool, whereas the second is characterised by a common thermal cycle, although the heat sources involved act on a workpiece at different geometric points» [32, p. 18].

This classification of the methods based on the «common thermal cycle» using two or more energy sources is incorrect, as the thermal cycle is undetermined in space and time. The laser-arc welding processes [33--41] are characterised by one specific feature, which cannot be explained by simple superposition of properties of the employed heat sources taken separately. This feature consists in increase of the coefficient of utilisation of energy of both laser and arc heat sources. With such a hybrid process it is more efficient to use the constricted (plasma) arc combined with the laser beam, located at an angle to each other or coaxially. During the last decade the E.O. Paton Electric Welding Institute offered several schemes for the hybrid processes. Investigations are conducted under the leadership of Prof. B.E. Paton to study characteristics and technological capabilities of different combinations of laser, arc and other melting sources. In particular, peculiarities of thermal processes, efficiency and temperature fields were studied, and recommendations for selection of shielding gases, etc. were worked out [39, 41].

The development of the «hydra-process» based on the use of three or more heat sources, having different physical origin and application, was a new stage of progress in the field of the hybrid plasma-arc welding technologies [42]. They include the plasma-arc welding process, which provides for utilisation of two TIG torches with tungsten electrodes and a plasmatron located between them. The impact on a workpiece by the sources may be of different kinds. Company «Munchengladbach» in Germany applied a combination of three TIG welding processes and a plasma-arc process for high-speed welding. All electrodes, a plasmatron nozzle with electromagnetic and gas stabilisation, and a shielding gas nozzle are housed in one torch. Control of the processes is synchronised. It is noted in one of the latest studies [1] dedicated to development of welding with two or more energy sources that this area has the highest promise. The hybrid processes based on the integrated action of the fusion and pressure welding processes also show promise. One of the key problems in this case is complexity of the devices used to implement the processes. Most often the equipment for the hybrid processes is a sum of the basic units of each of the heat sources, as well as of separate or combined power supplies with electronic control of process parameters.

During the last decade the laser-arc and laser-plasma welding processes have been developed most intensively. On the basis of experimental data, I.V. Krivtsun from the E.O. Paton Electric Welding Institute developed the theory of physical phenomena occurring in interaction of the focused laser beam and plasma of the electric arc. It was established that a special type of the gas discharge, the properties of which differ from properties of the conventional arc and from properties of the optical beam, may form in this system. Mathematical models of such a discharge in laser-arc plasma torches were developed. The application showed certain advantages [43--45].

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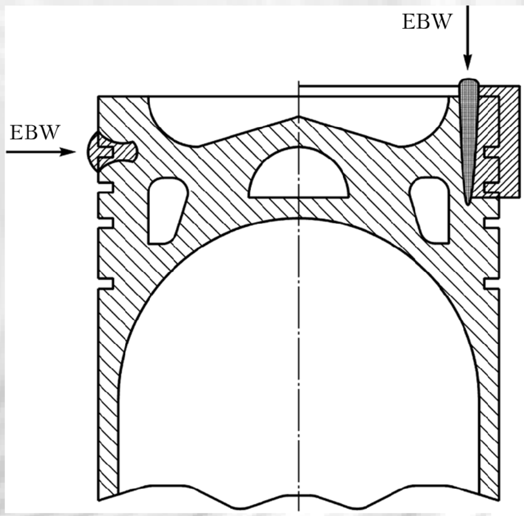
TECHNOLOGY FOR REPAIR AND RECONDITIONING OF WORN OUT PISTONS AND OTHER MACHINE AND MECHANISM PARTS

Modern technologies for repair and reconditioning of worn out machine parts and imparting them the initial or even high properties and technical characteristics become increasingly topical under the present conditions of growing shortage of raw materials and energy crisis.

For example, two versions of repair of worn out pistons are available for the ZIL-130 car and «Ikarus» bus pistons: in the first case it is cladding of the worn out cavity under the first compressor impeller using filler wire, and in the second – turning of the worn out piston head with subsequent welding of a band and its machining.



In both cases the repaired piston has higher characteristics of the deposited layer or welded band than base metal of a new piston. Therefore, this guarantees its renewed life not shorter than that of a new part.

Normally, the cost of repair and reconditioning is not in excess of 30–50 % of the initial cost of a new part. Cost effectiveness of the offered technology grows with growth of weight and cost of parts to be repaired.

Proposals for co-operation. Development of technical documents, transfer of know-how for the technology, technical consultations and engineering services in commercial application of the te-chnology.

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