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ADVANCES IN LASER TECHNOLOGY

Achievements in fundamental physics more than once served as the basis for construction of new heat sources for welding and related processes. During the last 20–30 years another new scientific and technical area has been formed in the field of the welding technology. This area is associated with lasers and characterized by extremely high rates of development.

Now lasers have transformed from an object of physical research into a powerful tool for welding, cutting and surfacing. A new branch of machine building has emerged, which manufactures industrial equipment for the respective technological processes and, in the first turn, technological lasers. The latter have a number of peculiarities, primarily a high power, which distinguishes them to advantage from many other types of lasers used for communication, medicine, information facilities and many other purposes.

Technological lasers are classified mostly by three indicators: operation mode (continuous or pulsed radiation), type of an active material (solid state activated glass or ion crystal lasers, gas lasers, semiconductor or diode lasers) and excitation method (optically pumped lasers, gas discharge lasers and lasers with electron pumping).

Technological lasers generate radiation which theoretically is superior to that generated by all other heat sources, including electron beam, in power per unit surface. Laser radiation can be used for welding and cutting of materials with a very wide range of physical properties, from the smallest thickness and to a thickness of several centimeters. In welding without deep penetration the travel speed can amount to ten meters per second! In this respect, laser welding have certain advantages over electron beam one.

The many year competition between laser and electron beam heat sources for welding applications turned out to be very exciting and fruitful.

Despite the fact that the efficiency of vacuum used as a shielding environment in welding was demonstrated many times, the need for substantial capital investments to build evacuation systems and the vacuum chamber proper is a serious factor in favour of choice of laser radiation, instead of electron beam. This is especially pronounced in laser welding of extended ship and aircraft multi functional monolithic 3-dimensional structures, based on the so called stringer panels, made from steel and aluminium alloys. Laser turned out to be beyond compare in manufacture of tailored blanks for car bodies and many other pieces.

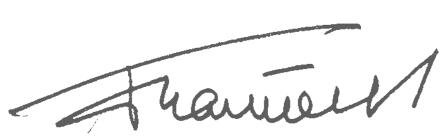
Laser has introduced radical changes into cutting of sheet materials, especially precision cutting. It opens up large prospects in the field of deposition of thin wear resistance coatings.

The efficient applications of combined welding processes: arc + laser beam and high frequency current + laser beam, have been recently reported. Our Institute is successfully developing a welding method which combines plasma and laser beam. A combined effect of these two heat sources has a particularly high manifestation in this case. There is no doubt that the hybrid processes using lasers will find wide application in welding industry.

Visitors of the last welding fair in Essen (September 2001) were highly impressed by demonstration of laser welding equipment and applications. Exhibits covered the entire range of potential applications of laser welding: from fully automated with computer control to the so called mobile (mechanized) welding, and from precision welding requiring binocular microscopy for tracking the process to high speed tandem laser arc welding of heat exchanging aluminium panels 10 mm thick.

The main factor that restricts application of laser welding is certainly a high cost of equipment. Hopefully, this situation will change to the better in the near future, in particular owing to construction and commercial application of high power diode lasers, which are much less expensive, small size and characterized by an incomparably higher efficiency.

This issue of our Journal, which we offer to your attention, is dedicated to description of achievements in the laser technology and its capabilities.



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LASER TECHNOLOGY AT A NEW STAGE OF DEVELOPMENT

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ABSTRACT

The state-of-the-art and prospects of development of laser technologies and equipment for welding, cutting and various types of hardening treatments are analysed. Extremely high potential of laser processes for advancement of modern science and technology in the most important industries is shown, and the national experience in this area is noted.

Key words: *welding, gas and solid-state lasers, micromachining, cutting of metals, laser hardening, surfacing, engraving, surface cleaning*

The first lasers emerged at the end of the 1950s — beginning of the 1960s. Today they have more than 350 different applications almost in all spheres of human activity. Among them materials treatment is the area where laser technology has gained the widest acceptance [1]. This technology is a very dynamic and self-sustained area of modern machine building and instrument making, having multi-billion (in dollar amount) turnovers in the volume of capital. The most efficient technological application of laser radiation is for micromachining (manufacture of microholes, slots, micromilling, etc.), location and spacing of blanks and cutting of materials, surface hardening treatment (hardening, alloying, surfacing, spraying, etc.), welding, marking, engraving, deposition and reading of coded symbols, running balancing, surface cleaning (removal of insulation, contaminants, radioactive materials, etc.), growth of three-dimensional objects, making of tailored blanks of sheet materials, and special laser treatment operations.

Based on orientation of this issue of the Journal to the particular subject matter, while analysing the state-of-the-art and prospects of development of laser technology the author gave a special consideration to problems associated with laser welding, cutting and different types of hardening treatment of materials.

Laser equipment. Today the most extensively used lasers are gas CO_2-lasers with a wave length of $\lambda =$ $= 10.6$ μm and solid-state YAG lasers with $\lambda =$ $= 1.06$ μm. Radiation power of the former amounts to 50–70 and the latter — to 2–4 kW. Drawbacks of CO_2-lasers include large dimensions, substantial consumption of very valuable helium and impossibility of using fibre optics for transportation of their radiation. YAG lasers have no such drawbacks, this accounting for their more frequent current application. Recently an increasing acceptance has been received by lasers which generate radiation in the ultra-violet range of electromagnetic spectrum (CO-, eximer-, metal vapour, etc.). Their short wave length (0.2–0.6 μm) provides a higher power density and efficiency of utilisation of laser energy owing to its better absorption by metal surfaces. Emergence of X-ray lasers will make it possible to increase capabilities of super-precision treatment, e.g. in building of micromodules for a new generation of computers [2].

Given that modern high-power lasers are comparatively low-efficiency power converters (their efficiency varies from tenths of a percent to several percents), developments of semiconductor (diode) lasers, the efficiency of which amounts to 90 % and higher, are considered very promising. Because of a very low power of individual diode lasers, the trend now is to combining them into a large matrix, which enables achieving the value of an integral power equal to 100 W and higher. A substantial increase in the efficiency of operation of the YAG lasers and decrease in their dimensions can be achieved also by using the diode lasers. They are applied for pumping active solid-state elements, instead of gas-discharge pump tubes. As a result, size of laser radiator with a power of 1 kW can be decreased to that of a shoe box [3].

Micromachining. The use of lasers for micromachining has been known since the time of their first emergence. Owing to specific properties of laser radiation characterised by a high concentration, electromagnetic energy can be localised to a considerable degree, which allows controlled removal of microscopic volumes of material and, thus, precision machining. At present, microholes with a diameter of up to several micrometers can be made in different materials, independently of their properties. This technology is used to machine precision holes in tool stones, diaphragms, fuel nozzles, various filters, special tools of the type of diamond and hard-alloy dies, and drawing dies for making synthetic fibres, etc. [1]. Productivity of making such holes, depending upon the material thickness, may amount to several thousands of holes per second. High-speed scanning of laser radiation can be applied for making complex-profile slots in different components of microelectronics, precision adjustment of resistors, etc. This technology is indispensable for precision slotting or scribing of superhard synthetic or natural materials [4].

The challenge of improving quality and precision of machining can be handled by using supershort laser pulses (nano-, femtosecond) and lasers which generate radiation in the ultra-violet and even X-ray range of electromagnetic spectrum. Also, this will allow mastering of the range of submicron (down to nano-) values of diameters of the holes and width of the slots which can be made using the laser beam.

Location and spacing of blanks and cutting of materials. The use of lasers for location, spacing and cutting is very popular now, as along with high accuracy and productivity of treatment they provide a substantial saving of materials owing to a very small width of the cut and a rational system of location and spacing of blanks, compared with traditional technologies [4, 5]. The efficiency of cutting of parts of a complex profile at a small-series production is much higher in this case than in conventional blanking of sheet parts. In the case of large-size billets of a complex profile with a large quantity of standard similar-type components (large holes, windows, etc.), machining may be performed using hybrid facilities of the laser–press type, thus enabling the high-efficiency utilisation of advantages of both processes: traditional blanking pressing of typical components and flexible laser cutting of complex profiles.

Laser location and spacing of blanks is extensively used in modern automobile industry, aerospace engineering, ship building, electrical engineering, agricultural machine building and light industry. In addition, rather specific applications of laser location and spacing are being developed now, e.g. in power engineering. For instance, at nuclear power stations it is often necessary to perform remote treatment (cutting) of various metal pieces for erection and repair operations at high levels of radiation. This treatment can be conducted very effectively by laser technology through transporting the laser energy via light guides to very large distances (up to 100–200 m) and using robotic systems with a remote control [6]. A striking example of specific capabilities of laser cutting was the development of a robotic laser system for dismantling operations to be performed on the «Shelter» object at the Chornobyl Nuclear Power Station. Owing to the use of contactless remote treatment, a self-propelled robot can be made as a very compact facility, which does not require much power for functioning. It can penetrate into hard-of-access locations inside the object to perform operations on disintegration of fractured metal structures and high-radioactivity lava formations for their further decontamination and burying [7]. This robotic laser system was developed by the Research Institute for Laser Equipment and Technology in collaboration with the Research Institute for Mechanics Problems «Ritm» of the National Technical University of Ukraine «Kyiv Polytechnical Institute» [8].

Surface hardening. Now this area is being very intensively developed in Ukraine, other CIS countries and Western industrialised countries, although the pioneering investigations in this field were carried out by our scientists, in particular the scientists of the NTUU «KPI» [9–11]. At the beginning the most intensive activity was in development and application of surface hardening without penetration of a material. This method, being very simple, allows microhardness of a surface material and wear resistance of parts to be increased from 2 to 5 times, avoiding thermal distortion of the parts, which is typical for traditional heat treatment methods. High efficiency of the process was demonstrated in local hardening of blades of various types of cutting tools (cutters, mills, drills, broaches, knives, scissors, blanking dies, etc.), many machine parts (crank- and camshafts, gear wheels, working surfaces of engine valves, hydraulic valve stems, etc.), various large-size parts of chemical and power engineering [12, 13].

In the last years a high interest in this technology has been expressed by developers of turbo-jet engines and super-power turbines (for local hardening of working surfaces of turbine blades). These critical parts operate under extreme conditions and, therefore, require extra hardening treatment [13].

Processes of local laser alloying, surfacing and coating make it possible to form a layer of a superhard material on the working surface of a part made from conventional structural steel, which allows a substantial improvement in performance of the part and an entire machine or instrument as a whole. These technologies are topical for any industry, but of a special interest they are to aerospace, motor engineering and other industries, where it is necessary to combine light weight and compactness of a structure with its high strength and wear resistance under extreme service conditions. For example, surface alloying of aluminium alloys with iron, silicon, copper and other metals makes it possible to substantially increase heat resistance of parts made from such alloys [14]. Performance of critical parts of titanium alloys in aerospace engineering can be increased in a similar way.

Despite a very high level achieved in the development of laser hardening technologies, there are still many problems which require solution in order to improve quality and raise productivity of these processes. In particular, because laser hardening is performed by using mostly high-power CO_2- and YAG lasers, this involves losses of laser radiation, caused by the fact that the major part of infra-red radiation generated by the laser is reflected from the metal surface. This problem can be solved through selecting the most efficient materials for absorbing coatings and methods for their deposition. The following materials are used at present for the above purposes: graphite paint, Zn, $Zn_3(PO_4)_2$, Si_2, Al_2O_3, C, Fe_3O_4 [15], and search for new materials is in progress.

Laser hardening technology is a multifactorial process, depending upon more than thirty different factors, which can hardly be controlled at a time. Therefore, it is advisable first to identify those factors which affect other factors and the process as a whole. The following factors can be identified as the main ones:

surface temperature, heating time and rate, as well as cooling rate. Surface temperature itself greatly depends upon absorbing properties of the surface. To control and raise the efficiency of hardening, it is necessary to find the possibility to control the absorbing ability of the surface and its temperature simultaneously with controlling the irradiation process. A device has been developed recently, allowing estimation of not only the absorbing ability of the surface during the process of its irradiation, but also its instantaneous temperature in the laser-affected zone [15].

One- or two-component compositions were used earlier for local surface alloying. Now laser cladding is performed using multicomponent compositions, primarily those which were initially developed for plasma cladding. Among them the most common compositions are the Ni-based ones. Main drawbacks of such compositions include high price, setting of the deposited layer in dry friction and high tensile stresses. The Research Institute for Laser Equipment and Technology of the NTUU «KPI» developed new compositions based on Fe–B–C alloys [16]. Owing to the iron base of these compositions, tensile stresses formed in the deposited layer are usually lower than in the case of using Ni-based compositions. Coating carbon steels with boron provides a much higher wear resistance, but leads to a decrease in ductility. The ductility loss was compensated for by adding silicon and chromium as extra alloying elements.

Tests showed the following advantages of the compositions developed for laser alloying:

• they are less expensive than compositions on the nickel (5–6 times) and cobalt (8–9 times) base;

• new compositions are non-toxic;

• hardness of the deposited layer is not lower than that of Ni-base alloys (*HRC* 62–63);

• new alloys have better adhesion owing to their similarity to the matrix material.

Improvement in quality of cladding using both existing compositions and new materials can be achieved by allowing for their thermal-physical properties and by bringing them closer to properties of the matrix material. The procedure developed for selection of compositions for cladding, allowing for the above factors, enabled a substantial decrease in the level of tensile stresses and, hence, the probability of microcracking [17].

Different combinations of laser technology and affecting a material by other energy sources can be used to increase the hardening effect of laser surface treatment. For example, specialists of the NTUU «KPI» studied and suggested for practical application the following processes to be combined with laser hardening:

• simultaneous plastic roll or ball deformation of an irradiated material;

• ultrasonic deformation, in which plastic deformation occurs due to the effect of a concentrator on the irradiated material vibrating at the ultrasonic frequency;

• treatment in liquid nitrogen, which provides an improved removal of heat from the irradiated zone (due to an increase in temperature gradient) and creates conditions for more intensive diffusion of nitrogen in the matrix material;

• laser cladding with electromagnetic stirring, which improves homogeneity of the deposited material and, therefore, quality of laser cladding [18].

Also of interest are the processes which are based on the combination of plasma treatment and laser effect on a material. Such a combination can be sequential (first plasma cladding is performed, and then laser radiation is used to improve adhesion characteristics of the deposited layer) or simultaneous (laser beam is fed through the plasmatron directly to the treatment zone, thus intensifying the plasma treatment process) [19].

Welding. Owing to a high power concentration and the possibility of a very flexible space and time control of the power, the laser beam has become a universal heat source for making permanent joints of different materials. At present it is used to join thin conductors with a diameter as small as several microns to metal microfilms. The laser beam can also be employed for welding steel parts more than ten centimetres thick, providing welded joints of a sufficiently high quality, which cannot be achieved by any other welding method. In addition to joining different types of steels, the laser technology turned out to be very efficient for welding aluminium as well as aluminium and titanium alloys. The possibility of ensuring a very high quality of welding of metal sheets of different thickness led to the development of a new technology for making tailored different-thickness blanks, meaning that location and spacing of primary blanks of metal sheet of the same thickness were done also by using the laser beam. This technology is very popular in motor industry and aerospace engineering. One of the new applications of precision laser welding is fixation of elements of magnetic circuits in electrical engineering parts, which leads to improvement of the technology of manufacture of high-quality electric-motor rotors, transformers and other similar products [20]. Laser welding opens up new prospects for quality thermal joining of parts made from plastic, ceramic and composite materials.

Among the problems handled by investigators of the laser welding process, one should note the following: making of a reliable system for monitoring of the welding process (several variants of diagnostics of the process using video equipment are available now); study of the capabilities of using new types of high-power lasers for welding; development of methods and instruments for non-destructive testing of the process; investigation into peculiarities of laser welding of materials of a differing nature, etc. Concerning the latter, a good example is joint research conducted by specialists of the NTUU «KPI» and the Beijing Institute of Synthetic Materials (China) to study the possibility of improving the efficiency and quality of laser welding of composite diamond-bearing segments to a steel casing of circular saws employed for processing of stones under the deposit conditions, without fluid cooling [21].

Marking, engraving, deposition and reading of coded information symbols. In view of the almost unlimited growth of ranges and output of different products (parts and components), identification of these products and deposition on them (or reading from them) of different volumes of functional information have become a pressing problem. In contrast to traditional methods, laser technology allows marking of any material by the contactless method and at a very high speed, ensuring the exceptionally high quality. It can be done not only on the surface, but also in the bulk of a material transparent for the laser beam. For example, identification number of a microscopic size can be made inside a very valuable diamond without any deterioration to its marketable state and with a guarantee that this number will be retained almost forever. The less exotic application of this process is marking of parts of microelectronics, electrical engineering, instruments and different types of tools, etc. Making of decorative inscriptions, figures and different types of engravings proved itself advantageous in jewellery, manufacture of souvenirs from metal, wood, glass, stone, plastics, etc. Lasers are applied quite extensively for making different types of relief inscriptions, signs on instrument panels, computer keyboards, etc.

Normal functioning of modern trading networks would be impossible without the use of laser deposition and especially laser reading of coded information on each product. Also, the laser technology provides a reliable on-line inspection, registration and control of goods flow circulation not only within an individual trading entity, but also within a trading system, region, country, etc.

Laser technology led to a revolution in the field of deposition, conservation and reading of audio and video information. Traditional forms of storing of audio (disks, magnetic tapes) and video information (magnetic tapes) are now swiftly replaced by laser compact disks. They can contain an enormous amount of information in the form of coded bits applied by the laser beam to a plastic disk, and provide an almost ideal quality of record and playback of this information. Until recently, its drawbacks included a limited amount of information which could be recorded in one disk and impossibility of deleting the recorded information or re-recording it. The first drawback has already been almost overcome. It turned out that the compact disk could be made of two layers, the upper layer being made transparent to non-focused laser radiation. Therefore, the required information is first deposited by the focused beam on the first layer, and then recording (or reading) of the information can be continued by shifting the focal spot to the surface of the second layer. As a result, the amount of the information recorded on such a disk is doubled [22]. Further investigations are in progress on manufacturing multilayer compact disk. Exciting solutions are emerging in the field of avoiding the second drawback. In particular, a special material can be used for the manufacture of the compact disk, which can restore its initial properties under conditions of extra photothermal treatment, i.e. the old record can be deleted and a new information can be recorded instead of it. Other possibilities of increasing the efficiency of using laser compact disks are also studied.

Dynamic balancing. Some modern high-precision parts have units which must be treated by a specific operation — dynamic balancing, i.e. precise removal of an unnecessary mass from the surface of a unit or part rotating at a high speed, to ensure stable operation of the product. Such parts include ship and aviation gyroscopes, high-speed electric motors, etc.

With traditional methods of balancing a location of unbalance is first determined and then this unbalance is removed as a rule by machining from the part (unit) in the quiescent state. The laser technology allows the operation of determination of location and amount of unbalance and the operation of precision removal of the unnecessary unbalanced mass to be combined in one process. This provides substantial saving of time (1–2 h), as it takes up to one hour for some critical instruments to achieve working conditions (several tens of thousands of revolutions per minute) and the same time to stop. The use of laser dynamic balancing does not only yield a substantial saving of time, but also provides a high precision of removal of mass (to a few milligrams or even tenths of a milligram).

The developed systems of laser dynamic balancing enabled considerable improvement of quality of gyroscopes, high-speed electric motors, etc., and, therefore, increase in reliability and extension of service life, as well as a substantial reduction in their manufacture cost [23, 24]. Further improvement of the technology can be achieved owing to application of the more efficient types of lasers, upgrading of the systems for automatic location of unbalance, etc.

Surface cleaning. This process has been intensively developed in the last years. Whereas until recently only laser removal of insulation from the ends of wires prior to their connection to appropriate electrical (electronic) devices has been widely spread, now more and more extraordinary and even exotic applications are emerging.

As it is, removal of insulation is a very efficient process: fast, readily controllable and contactless (causing no damage to a conductor). This is very important for superthin microconductors and various microelectric parts. The high quality of cleaning is achieved owing to a high absorbing ability of various organic materials (such as polymer insulating coatings) under conditions of their irradiation by the infra-red beam of lasers with a wave length of $\lambda = 10.6$ or 1.06 μm. This technology is employed also for cleaning of surfaces of critical parts from industrial contaminants, different types of surface inclusions in a material, etc., instead of traditional chemical cleaning methods.

The possibility of utilising the cleaning effect of laser radiation stimulated the development of environmentally clean technology for removal of different types of old paint coatings from large-size airfoil surfaces of aircraft, helicopters and spacecraft. Traditional technologies for cleaning the surface from paint are of low-productivity and environmentally hazardous. In the case of using a gas torch, it is hard to localise the heat effect on the surface treated, the process is difficult to control and involves the risk of fire. Various chemical methods of dissolution and washing out of paint deal with use of toxic materials, which can hardly be recycled further on. The quality of treatment is difficult to guarantee, because old paint and chemicals used for washing out may remain in mircocracks, pores, etc., which may lead to further development of a defect.

Laser technology allows removal of old paint and primer from the surface of a part without any damage to the base material. Modern types of lasers, video systems and robotic facilities can be used to build a high-productivity laser complex with a feedback to enable adaptation of conditions of removal of a paint layer depending upon its type, thickness, colour, etc. [25, 26]. In the case of using a laser with a power of up to 6 kW, a prototype of the facility can ensure productivity of surface treatment equal to 92 cm^2/min. In addition to the above positive features, laser technology makes it possible to very effectively detect leading cracks in critical zones of a structure and, hence, prevent development of emergency conditions.

Considerable recent progress in nuclear power engineering resulted in a pressing problem associated with cleaning of surfaces of various parts from radioactive contaminants. Laser technology can offer solution to this problem as well. Scanning the contaminated surface by the focused laser beam provides removal of radioactive materials due to their local dosed evaporation, further suction from the laser-affected zone and recycling in a special storage.

There are cases where it is necessary not to remove a radioactive contaminant from the surface but, on the contrary, fix it reliably to prevent pollution of radioactive materials (dust). This can also be done using laser radiation, but in the mode of penetration of the surface layer together with the radioactive dust. Therefore, the radioactive dust can remain for ever on the laser beam treated surface of metal, reinforced concrete, brick, ceramic roof, etc. [7, 27]. With a traditional technology this fixation was achieved using polymer coatings, which decomposed (fractured) under the atmospheric effects, thus leading to a dangerous spread of the radioactive dust.

Growth of three-dimensional objects. The classical technology of manufacture of a part (item) in industry provides for removal of excessive material from a billet to ensure the required shape, size and quality of the part. Progress in laser equipment and emergence of modern fast-response computers with an enormous memory capacity made it possible to develop the fundamentally new laser technologies for making parts of a complex spatial configuration, which provide element-by-element and layer-by-layer growth of a material in accordance with an image formalised in the computer memory. Available now are very many diverse methods for realisation of the processes, which can be found in a special literature and bear different names: optical fabrication, rapid prototyping, 3D-component forming, solid freeform forming, stereolithography processing, laminated object manufacturing, directed light fabrication, selected laser sintering, material accretion processes, etc. [28, 29]. Polymers, paper or cardboard tape treated with an adhesive composition, metal strip with a low-melting point coating, metal powder or special composition, etc. can be used as materials for realisation of this technology. Of special interest is the method of synthesis of a 3D-part from metal powder materials using a scanning laser beam. With this method a powder of one composition or a composition of different powders mixed in different proportions can be fed to the laser-affected zone to provide special properties of a part in the required locations. Therefore, different properties of components of a part in accordance with different designed service conditions can be provided as early as at the stage of manufacture (growth) of the part. This makes it possible to eliminate the need for subsequent deposition of a coating, cladding, local alloying or other additional operations typical for traditional technologies of manufacture of parts.

The processes of growth of 3D-objects are now gradually coming out from the stage of experimental verification into the stage of commercial application. This technology is particularly topical for such dynamic industries as aircraft engineering, motor industry, electronics, tool-making industry, space engineering, etc. As compared with traditional methods of design of parts and units, the new technology of growth of objects at the US Company «General Motors» allows saving of up to 60–80 % of time and money. For example, in manufacture of a model of the locomotive transmission gear box casing the time consumption was reduced from 6 months to 400 hours (16.6 days). Laser technology enables a very prompt realisation of an enormous diversity of complex 3D-parts of any design at minimum costs, allowing for the boldest fancy of a customer (buyer).

One of the efficient application fields of the new technology is manufacture of components of die tools, especially repair of die cavities and moulding dies for manufacture of large-size parts [30]. Interesting prospects are opened up by using it in medical practice, particularly in preparation and conducting of surgical operations for remedy of traumatic consequences or pathology. For instance, if necessary to conduct a neuro-surgical operation, a plastic 3D-model of a skull, which shows real consequences of trauma, is grown by the tomography data to develop strategy and tactics of such a complicated operation. A surgeon identifies in detail all stages of the operation using this model and, therefore, increases the guarantee that the operation will be a success. Even now the time for making the plastic model by the tomography data is less than 6 h [31]. This time can be further reduced, providing that more perfect software and increased-capacity computers are available.

One of the most important peculiarities of the suggested laser technologies is the possibility of separating different stages of development of a part in time and space. The computer information on a designed part (CAD-information) can be elaborated in one city at a certain time, and then transferred via telephone or satellite communication lines to the other place, e.g. to a workshop equipped with special hardware for laser synthesis of parts. Just imagine transfer of such an information to a future space interplanetary station at which there is a need to manufacture a spare part for the station hardware. Then it will be enough to transfer via a satellite communication from the Earth a formalised description of the part (instead of sending a finished part by a transport rocket), and make it on the station using a compact multifunctional laser facility.

Formation of parts of a complex spatial configuration from sheet metal. The possibility that heat energy input into the laser-affected zone and its displacement over the surface of a workpiece can be controlled very precisely resulted in the development of a technology for programmed changing of shape of a sheet metal due to thermal deformations generated by the laser beam. This technology, avoiding the use of traditional expensive deformation tools (punches, dies, moulds), can be used to make tubular pieces, wavy surfaces, and bend metallic materials according to a program [32]. This technology has proved itself advantageous in cases where it is necessary to make a small batch of complex-configuration parts from a metal sheet, and where design and manufacture of complex-shape deformation tools is economically unjustified. Reported is an experimental use of radiation of a high-power CO_2-laser to change spatial configuration of a rolled steel plate 25 mm thick [33].

Special laser treatment operations. Specific features of utilisation of the laser beam as a versatile tool make it possible to keep offering new technological applications for lasers. Combination of laser technology with other processes yields a substantial effect. For example, the use of laser for local heating of a material layer prior to removing it by a mechanical cutting tool makes the process of machining of superhard materials much easier and extends life of a cutting tool [34]. With classical cutting the laser can be effectively used for grinding of discharge chips, e.g. in drilling deep holes, which enables a substantial rise in productivity of the process of their machining by gun drills. The use of lasers for dressing of diamond-bearing abrasive wheels reduces losses of synthetic diamonds, increases productivity and accuracy of diamond treatment of superhard materials. Exceptional prospects are opened up by combining laser technology with electrochemical, electric-discharge, ultrasonic and other types of materials treatment.

Potential of technological application of laser radiation is far from being exhausted, which is evidenced by results of numerous recent publications. Further development of laser equipment and technology allows a manufacturer to receive substantial benefits under conditions of severe competition in the modern global economy.

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LASER TECHNOLOGIES IN SHIPBUILDING — REALITY AND PROSPECTS

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ABSTRACT

Experience of development and application of laser technologies in shipbuilding, gained in Germany, is generalised. Comparison of the effectiveness of application of laser technologies and arc processes is made. Examples of the most effective laser applications in shipbuilding are given.

Key words: *laser technologies in shipbuilding, laser welding, laser-arc welding, surface treatment, cost effectiveness*

Laser technologies, applied in many areas of materials processing, are regarded to be the most effective and promising. Laser allows cutting, welding and processing the surfaces of various materials at a high level of technology and cost-effectiveness. As indicated by forecasts, only those sectors of the economy, that will extensively use laser technology, will be competitive on the world scale in the future. It should be noted, that Japan uses as many lasers for material processing, as both Western Europe and USA. Application of laser welding showed, that in fabrication of regular ship structures, the efficiency of manufacturing panels with up to 16 m weld length increases by 100 %, as a result of a considerable increase of welding speed, as well as a low heat input, and, hence, cost saving due to elimination of subsequent manual treatment, for instance, straightening, etc.

Laser technology introduction into shipbuilding began in FRG already at the start of 1990s, in particular, in fabrication of individual parts, including panels [1], and for processing the surfaces of seaborne machinery. Investigations have been conducted since that time with the aim of the process certification both for welding [2], and for surface treatment, i.e. prerequisites for its introduction are created. European classification societies have taken a decision on issuing unified guidelines on laser welding application in shipbuilding. Research is being intensively pursued in Germany, which is vividly demonstrated by laser centers. In particular, Fraunhover Institute of Laser Equipment in Aahen, Institute of Applied Laser Technologies in Bremen, Bavarian Laser Center in Nuernberg-Erlangen, Laser Center in Hanover, as well as similar institutions in Berlin, Hamburg, Neumuenster and other cities.

In addition to the high interest from the Ministry of Education, Research and Technology, as well as the centers on research results introduction into the German shipyards, Shipbuilding Research Center, German Lloyd and manufacturers also continuously provide the initiative for solving the problem of laser application in shipbuilding today and in the near future.

State-of-the-art. Data on the efficiency of laser welding technology (Figure 1) were given in the report of Prof. Herziger in the meeting of the Shipbuilding Engineering Society in Berlin in 1992 [3].

In addition, comparison is continuously being made with the most advanced highly efficient welding processes developed, that provide a welding speed of up to 6 m/min and deposition rate of up to 16 kg/h (high-speed arc welding, welding in a four-component shielding gas and twin-arc welding). Laser sources are being continuously improved, for instance, output beam power already now reaches 45 kW (Figure 2).

Known is a comparatively new type of laser, developed allowing for the specifics of shipbuilding, as by no means the least important application (Figure 3). It features the best technical parameters and characteristics in terms of beam quality, weight/power ratio and outer geometrical parameters. Commercially available turbolasers have stable output power of 20 kW, and a 30 kW turbolaser operates under the laboratory conditions. Work goes on to increase the output power, the intent being to connect several modules to increase the efficiency to 40–

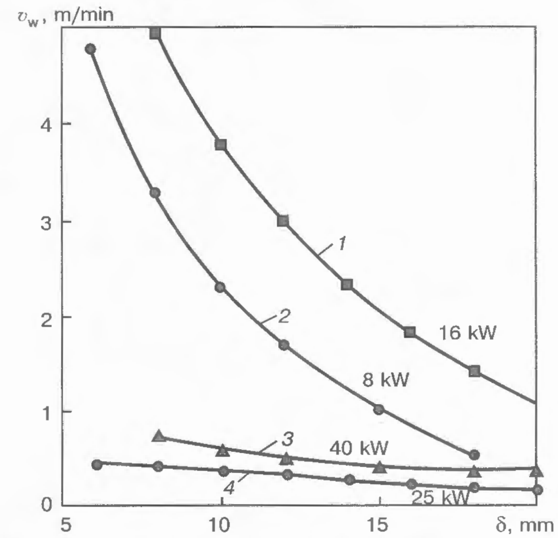

Figure 1. Welding speed, depending on thickness of metal welded (structural steel) for different welding processes [5]: *1, 2* — laser; *3, 4* — submerged-arc with two wires and one wire, respectively

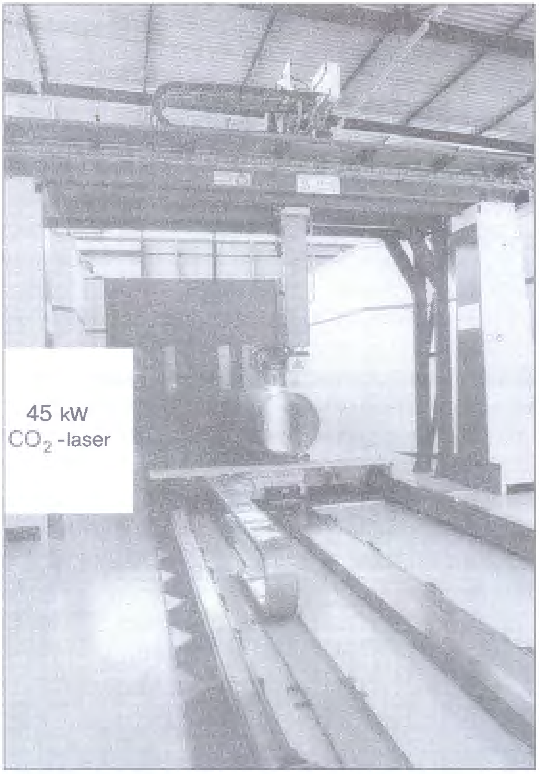

Figure 2. CO_2-laser of 45 kW power with transverse pumping and six axes processing center (Institute of Welding Equipment in Matz, France)

60 kW. Figure 4 shows the achievable penetration depth, depending on welding speed.

Such a high output power of the laser is usually used to achieve a high welding speed. In Figure 4, however, it is shown, that at a relatively high speed it is also possible to weld thick metal, comparatively rarely used in shipbuilding.

Technological problems are encountered in the upper thickness range. There is a high probability, that it will be possible to solve them on the basis of further research and development (multi-beam and laser-arc welding)

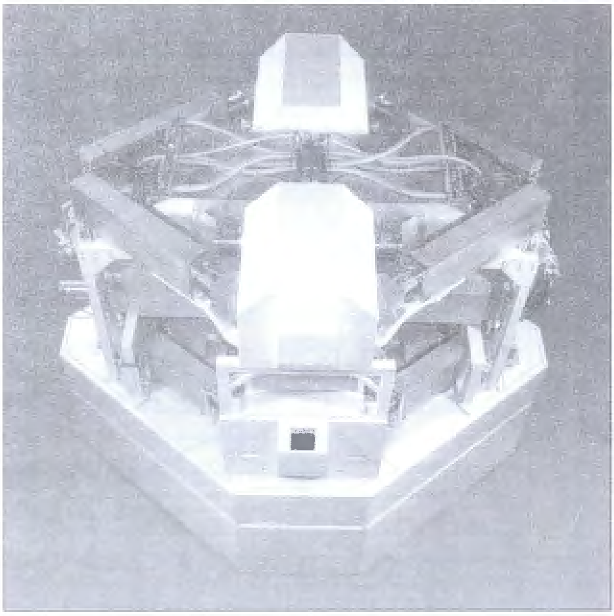

Figure 3. TRUMF laser, TLF 2000 Turbo

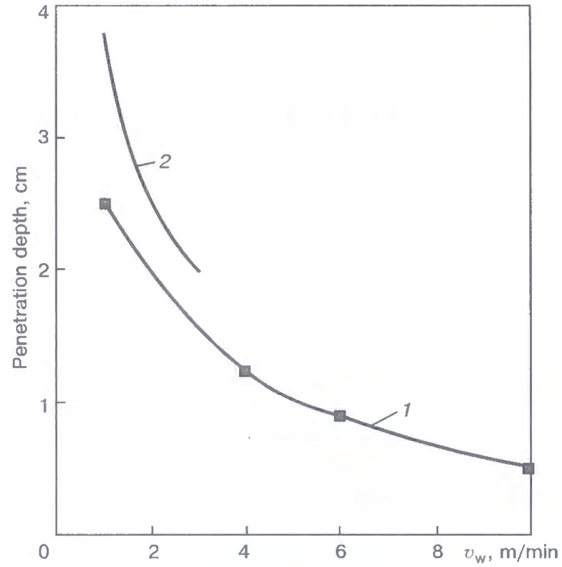

Figure 4. Penetration depth at beam output power of 30 (*1*) and 45 (*2*) kW, depending on welding speed

[4]. High-speed welding of up to 12 mm thick plates has already become a reality now, so that direct introduction of this process into industry is possible, which it is rational to implement in the near future in view of the growing international competition.

Laser technologies in shipbuilding are becoming applied in such companies as Mailand (Italy), Riva Techint, as well as Mayer-Werft in Papenburg. This will be soon followed by laser equipment mounting in Odence and Fincantieri Concern in Venice. German shipyards are conducting intensive preparation for laser application in shipbuilding. Riva Techint Company, in particular, is working to increase the penetration depth and welding speed. Combination of 10 and 17 kW laser beams, provides a summation of output powers on the item, i.e. 27 kW. In this experimental set up butt and fillet welds were produced by the order of Fincantieri Shipbuilding Concern. The whole system is made as a mobile gantry with the working zone of 3.50 × 52.00 m.

Three-dimensional processing systems with a built-in CO_2-laser are very seldom larger, than the size of a car. This limitation is mainly the result of the length of the reflected CO_2-laser wave (10.6 μm) and the need to bring the beam to the processing location through a system of mirrors. Applied in industry are processing systems with a moving item, running beam («flying» optics) or hybrid systems. Solutions, based on flying optics, provide a high dynamics of the machine operation, due to its lightweight structure.

However, any widening of the processing field has physical limits. Divergence of Gaussean beams is responsible for variable illumination of the focusing optics, depending on the beam path. In order to guarantee the stability of processing results, telescopes and adaptive optics are used, that should be designed, allowing for the beam path and free passage of the beam through the gantry, while providing continuous illumination of the focusing optics. Such systems with path length of up to 64 m were developed and tested.

Table 1. Relative cost depending on plate thickness

Parameter	*Workpiece*	
	Ferry	*Container ship*
Water displacement, t	7500	14000
Average plate thickness, mm	7–8	16–20
Relative cost, %	18	5

Laser welding as a highly effective joining method in fabrication of ship hulls. Significant quality improvement is always associated with higher energy density. This is proven by the history of welding processes development: forge welding – gas welding – arc welding – beam welding. Increase of energy density brings about the following effects: higher welding speed; lower heat input, and, hence, smaller amount of heat applied to the item; lower strains; shortening of the processes of post-weld treatment, for instance, flash removal, fitting, straightening; higher precision of manufacturing; general increase of efficiency.

According to statistical data, the potential saving, that is annually achieved as a result of higher precision of parts and shortening of stages in the general process, is $830,000 in the case of fabrication of two tankers of 50,000 tons displacement.

The data in Table 1 shows a considerable cost reduction in application of laser welding, especially in the case of sheet products. Our own analysis and evaluation demonstrated, that if the ship hull were made with laser welding application in shipbuilding, it would mean ≈ 50 % saving of welding costs. This again indicates, that improvement of the accuracy of part and component fabrication is very important in shipbuilding technologies.

According to Japanese studies [5] the accuracy of 4–6 mm/10 m in marking and cutting involves labour consumption of 50–80 hours per ton of steel, while precision increase up to a level of less, than 2 mm/10 m reduces the cost in ship hull fabrication to 25 hours per ton of steel. Strains and the associated deviations from technology occur mostly in thermal cutting and welding, while laser technology allows minimizing them. Consistent application of beam systems contributes to production costs of 15 hours per ton of steel becoming a real goal now.

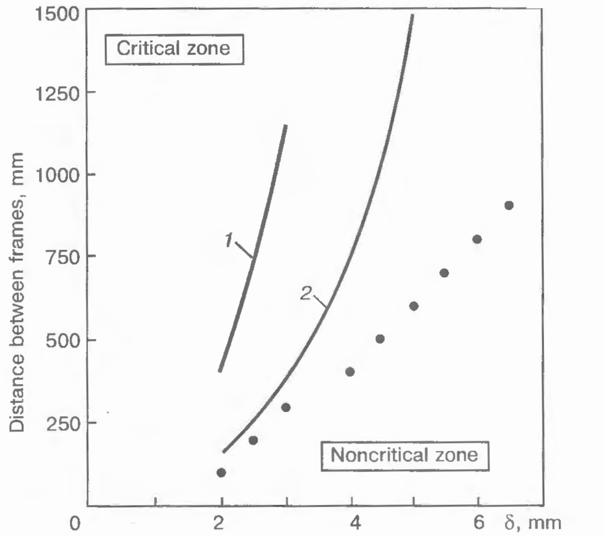

Figure 5. Comparison of critical distances between the frames in laser (*1*) and MAG welding (*2*) (circles show zone interfaces)

Results of investigations in the Training-Research Center of Meklenburg-Vorpommern Land demonstrated the advantages of laser systems application in fabrication of flat load-carrying structures with stiffeners. A lower heat input, resulting from a higher speed of laser welding, leads not only to reduced deformations, but also to a high stability of item form. Figure 5 shows the zones, where we can anticipate buckling due to loss of the form stability.

Comparison between MAG and laser welding demonstrates, that in case of the latter either the panel thickness can be reduced, or the stiffener spacing can be increased without any loss of stability. In addition to weight reduction, also a reduction of production costs is achieved, due to smaller number of welds (if this does not contradict strength analysis or boundary conditions of the structure functioning).

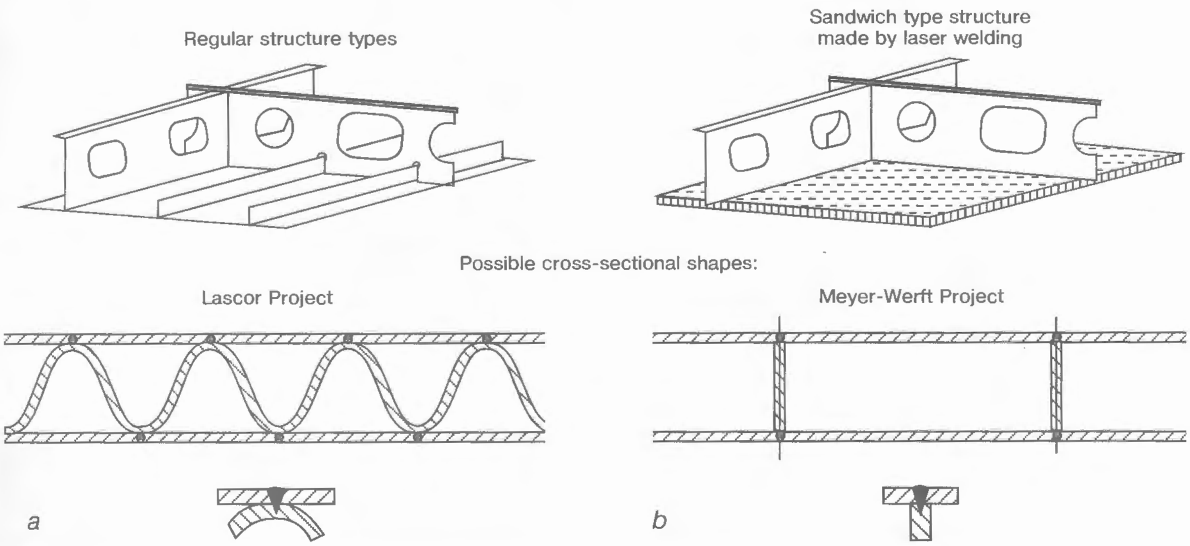

Figure 6. Variants of fabrication of cassette panels (flooring): *a, b* — welds made by laser welding

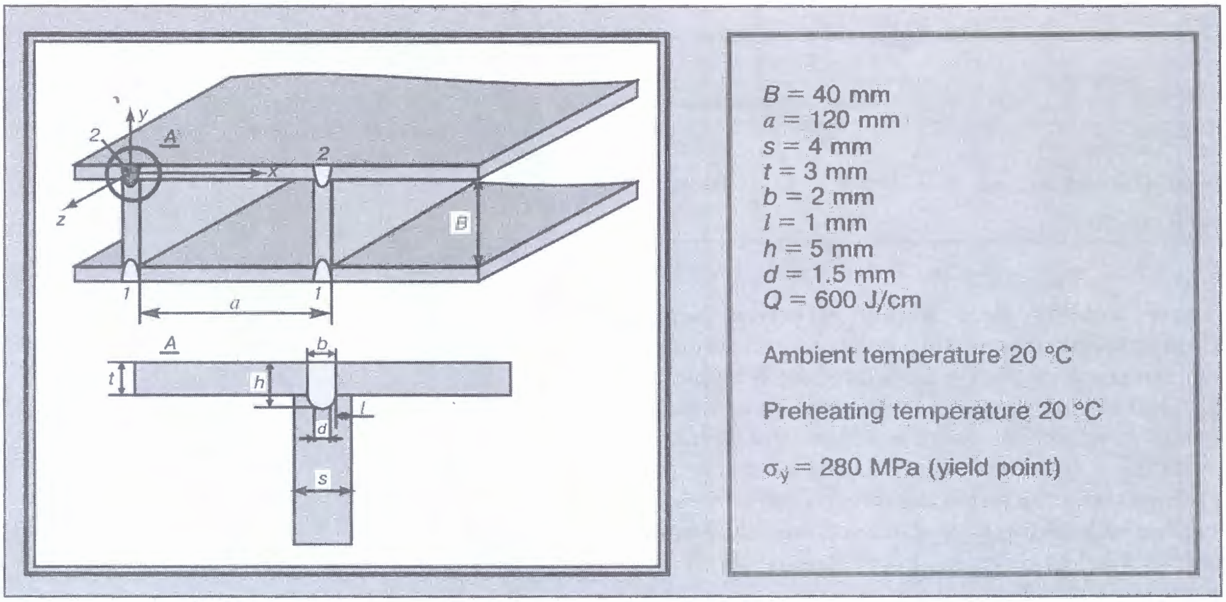

Figure 7. Software to calculate internal stresses and strains

In addition to simple replacement of the regular welding processes, the advantages of the new technology in terms of structure adaptation are becoming more and more obvious. For instance, it concerns the variant of cassette flooring in a Meyer-Werft shipyard in Papenburg, the «smoothness» of the flooring being due to buried tee joints (Figure 6). In the Training-Research Center in Rostok there already are programs on deformation behaviour of materials in laser welding, that can be used to optimize the whole process (Figure 7). Such structures, adapted to laser welding, are made using light-weight elements. Still another major advantage is the fact, that many preceding and subsequent operations are thus eliminated.

So, in this case, no straightening or mounting counter weights is required, this simultaneously promoting weight lowering. Thermal and sound insulation measures are simplified, as the space between the upper and lower sides of the cassette panels is used for mounting the separated wire systems.

In Great Britain the intent is to apply such design geometries for aircraft carrier landing decks, that guarantees them a high local strength and rigidity [2].

Standard structures can be batch-produced cost-effectively for a multitude of other ship elements, for instance, foundations of various auxiliary machines, pumps, separators in the engine-room, etc., as well as light-weight mobile partitions, ferry quays, and even hatch covers. Programs for computation of low-

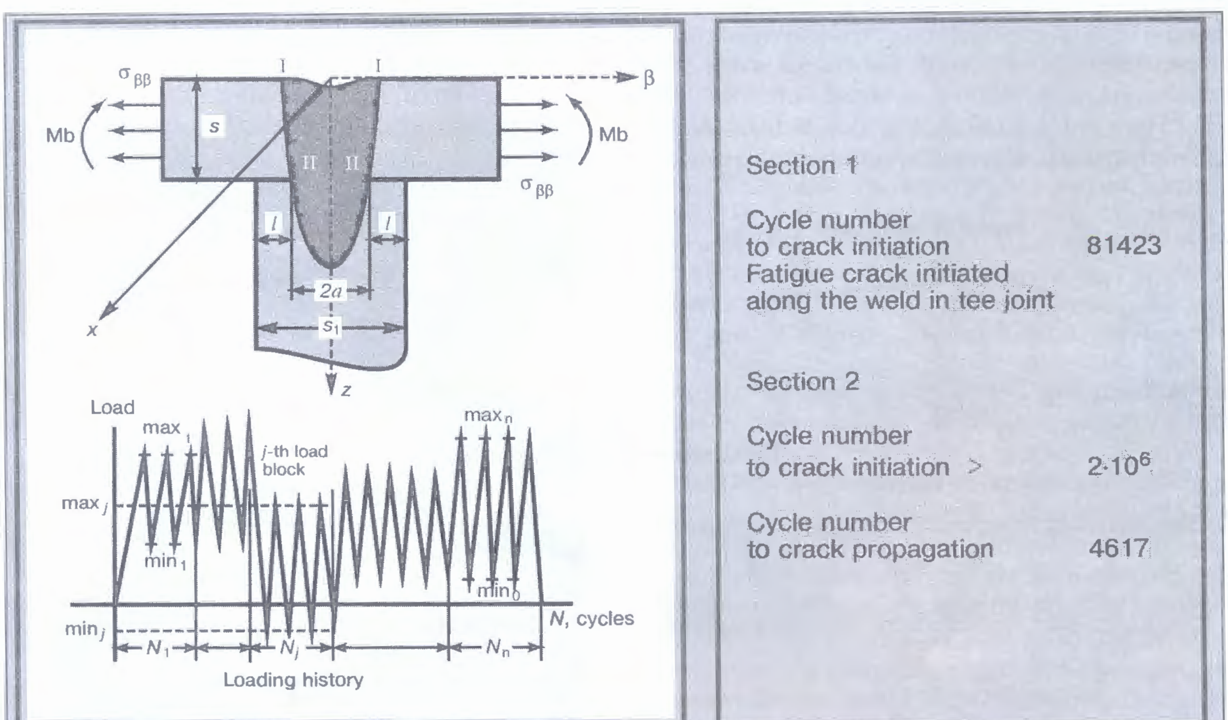

Figure 8. Software for calculation of low-cycle strength of structures with buried tee joints

cycle fatigue of structures with buried tee joints have already been developed (Figure 8).

Application of the currently available laser beam generators can be expanded by combining them with the regular welding processes. A multitude of process variants, allowing greater thicknesses to be welded, is being developed now, that have process advantages, in particular, increasing the welding speed. This pertains to combining laser systems with plasma, MAG or SAW. Let us enumerate just the following: greater maximal depth of penetration; higher welding speed; minimizing the welding heat input; improvement of weld properties; higher loading for the available units by their retrofitting, etc.

Macrosection of the joint, produced in combined laser and SAW of shipbuilding plates 20 mm thick, and studied in the Training-Research Center of Meklenburg-Vorpommern Land, is shown in Figure 9. Such a combination of welding processes is achieved by fitting the modern gantry for SAW with additional laser heads. It is just necessary to additionally mount a sensor-controlled precision axle. Considering, that in welding from one side, it is technically difficult to provide the weld root protection by the backing, in the combined process it is possible to apply high-speed laser welding up of the root. Edge preparation accuracy, sufficient for the laser process, is guaranteed by milling machine tools, currently applied in shipbuilding. Laser cutting proper, however, provides the edge preparation accuracy, comparable with the mechanical methods. Laser process speed allows welding and cutting to be performed in one laser processing center, depending on the scope of production.

While edge preparation can be performed with the required accuracy, maintenance of the maximal admissible tolerances during the process is somewhat difficult. Thermoplastic processes during welding lead to a great widening of the gap, that should be taken into account, considering small defect tolerances in laser welding. Mathematical simulation showed, that this problem can be solved by selection of clamping devices and conducting the process in an appropriate manner (Figure 10).

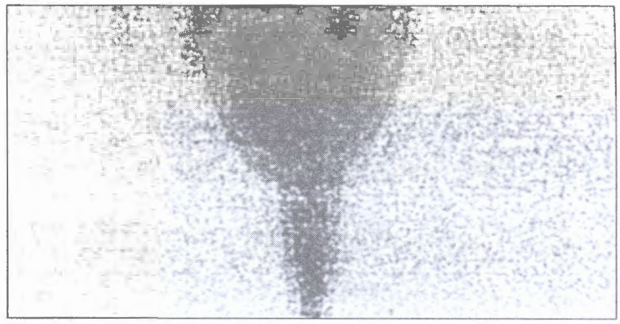

Figure 9. Macrosection of a combined laser + submerged-arc weld (d = 20 mm)

When a decision on laser welding application is taken, the decisive factors are cost of one linear meter of the weld, of each panel and, ultimately the cost to apply a new process, compared to welding in a conventional unit. Taken for comparison, is a sample of a panel, made of 4 plates (3 × 16 m, 12 mm thick) and 16 strips [6]. The length of butt welds to be made is 48 m, fillet weld length being 256 m. The cost to make 1 m of butt weld, allowing for welding speed at the respective power is given in Figure 11, and the cost of a fillet weld — in Figure 12.

When butt welds are made, the advantages of laser welding over SAW are clearly manifested only at process speed higher, than 0.7 m/min, while in welding of fillet welds the advantages in terms of cost are obvious in the entire parameter range. Additional cost prior to welding and after it, is not taken into account. With optimal design of the gantry for laser welding, the optimal depreciation rate was calculated to be 1.5 years.

Technique of laser processing of surfaces in shipbuilding during fabrication and repair. The aim of laser processing is achievement of specific properties on the surface, for instance, high wear resistance or corrosion resistance. Given below are some cases of laser technique application for surface processing. These are ship engine gears of up to 2000 kg weight.

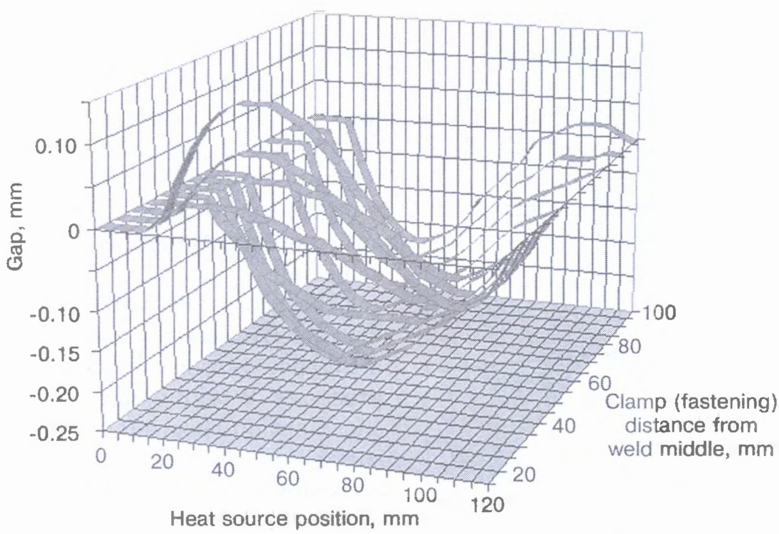

Figure 10. Dynamics of the welding process at clamping distance of 100 mm in the welding direction, heat input of 6.8 kJ/cm^2, v_w = = 1.8 m/min

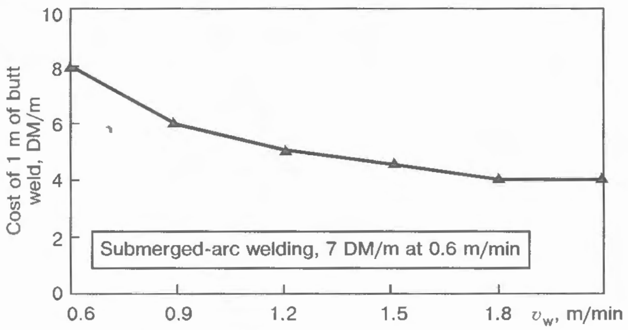

Figure 11. Cost of 1 m of butt weld, allowing for welding speed at laser power of 10 kW

Table 2 gives the list of processing operations and power consumption in regular martempering, compared to laser quenching.

The effect of rationalizing the quenching process is due to replacing double heating, performed in the furnace at 335 kW power for several hours in the regular quenching process. In terms of power consumption in this example the saving is 5667 kW/h per gear.

Material saving effect is achieved due to a much smaller item deformation, compared to martempering (owing to minimal heat input). Material removal in teeth grinding after quenching varies in the range of tens fractions of a millimeter, unlike large gears, subjected to martempering (1–2 mm). Laser quenching of the surface is a locally limited processing, that is conducted only where hard surfaces are functionally required. In regular furnace martempering of large gears the entire surface is saturated with carbon. Regular quenching is required to be preceded by removal of the carbonized layer several millimeters thick from the sides of the teeth being quenched. No such material loss is found in laser quenching.

In addition to gear quenching, the process of coating a piston head for ship diesel engines should be empirically considered. In Europe the annual demand for these products, new and designed to replace the worn ones, is 4500 pcs, of which about 2400 pcs are reconditioned. In case of coating application, the main problem in service consists in wear of the piston ring groove edges. Hard Cr-plating of these edges is performed, to extend the service life. This is an electroplating process, where the maximal thickness limit is 0.3–0.4 mm. Hence, the limited service life of

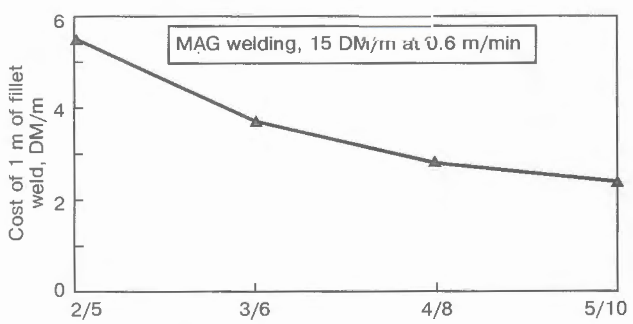

Figure 12. Production costs per 1 m of fillet weld, allowing for welding speed and power, plotted on abscissa axis (numerator gives welding speed, m/min; denominator — power, kW)

Table 2. Process operations and power consumption in gear quenching

Operation	*Martempering*	*Laser quenching*
Turning	Yes	Yes
Material control	Same	Same
Marking	»	»
Drilling	»	»
Tooth milling	290.4 kW/h	357.5 kW/h
Technical control	Yes	Yes
Mechanical work	Same	Same
Carbonization	2791.1 kW/h	Not required
Material control	Yes	Same
Surface cutting out ~90 %	276 kW/h	»
Drilling	Yes	»
Quenching	2613 kW/h	~336 kW/h
Material control	Yes	Yes
Sand blasting	Same	Not required
Turning	»	Same
Cutting-off with the polishing wheel	»	»
Marking	»	Yes
Drilling	»	Same
Cutting-off with the polishing wheel	440 kW/h	50 kW/h
Technical control	Yes	Yes
Material control	Same	Same
Mechanical work	»	»

~10,000 h. In terms of technology the limit admissible wear of the edges is 0.9 mm. After 0.4 mm of the chromium layer is lost, wear to the maximum admissible value of 0.9 mm occurs instantly, after which restoration to the initial condition is again required. This so far has been performed, using a surfacing process, requiring high consumption of material and power [7]. Laser surfacing technology allows applying layers of various wear-resistant materials up to several millimeters thick on a limited functional surface of piston ring groove sides, thus minimizing the wear, without any abrupt jumps. The first coating was applied on «Nordhausen» ship in 1989. Testing showed, that the service life of up to 30,000 h can be anticipated, although a life of 40,000 h can be also achieved.

The process of reconditioning a piston that has developed maximal wear, is shown in Table 3. A great difference is observed between the reconditioning processes. Working operations, related to high power consumption (heating, stress relieving by annealing, surfacing), and, therefore, to considerable material consumption are eliminated (no need to remove 25–30 kg of materials and again fill this space or make new circular grooves). If the laser process is used for coating new piston grooves, laser surfacing process is

Table 3. Comparison of piston reconditioning technologies

Regular reconditioning	*Laser reconditioning*
Groove cutting out	Cutting out a wavy groove
Welding of a buffer and wear-resistant layer	Laser surfacing of groove edges
Stress relieving by annealing	Groove edge grinding
Crack monitoring	Crack monitoring
Cutting out piston ring groove	
Groove edge grinding (preparation and Cr-plating)	
Cr-plated layer grinding	

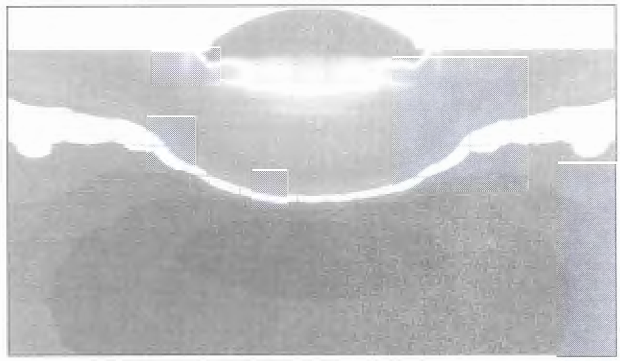

Figure 13. Inner longitudinal stresses in the bead deposited by a laser

not needed at the first stage. Simple overlapping of the areas of the circular groove and application of piston ring interference fit is sufficient.

In case of hard Cr-plating we have an extremely toxic and ecologically unsafe process. Its replacement by the laser process would allow completely eliminating the emission of toxic gases and vapours. A considerable reduction of heat input allows reconditioning piston heads that have so far been regarded as non-repairable. There is no need to make great numbers of new pistons to replace the worn ones. In addition to the two above-mentioned examples, it is also possible to mention reconditioning of cross head pivots and piston rods.

Optimal process parameters are determined by simulation to reduce the scope of preliminary work. Figure 13 shows development of internal stresses in laser welding at optimised process parameters.

In conclusion it should be noted, that the question of the prospects for laser technologies application in this area can only be given an unambiguously positive reply. Industrial application of the laser has already been implemented and this was the driving factor for changes in production of ship hulls and machines. A thorough study of the development process in Italy, Denmark, as well as overseas allows laser technology application to be highly recommended to German shipyards.

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PROSPECTS FOR USING LASER TECHNOLOGIES IN INDUSTRY OF UKRAINE

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ABSTRACT

Positive properties of thermal laser technologies, such as cutting, welding, heat treatment, cladding and alloying, are described. Prospects for using laser technologies in industry of Ukraine are shown. Expediency of further development of some ingenious scientific-and-technical developments in the field of laser technologies, e.g. amorphization of metal surfaces is noted.

Key words: *laser technologies, equipment, process fixture, tests of hardened parts, commercial application, application examples*

Thermal laser technologies (TLT) include cutting, welding, heat treatment, surfacing, marking, etc. Scientific principles of these technologies were elaborated earlier [1]. All of them are characterised by high productivity (linear speed of treatment amounts to several meters per minute), rapid transition from one mode to the other (e.g. from marking to cutting), insignificant heat input into a workpiece and high level of automation. However, the serious drawback of TLT is a high cost of the equipment involved.

Modern thermal laser technologies are characterised by a rapid advancement and wide acceptance in different countries. Main factors that favour their swift development are research of the operational capabilities of a high-power laser radiation in materials treatment, elaboration of not only principles of the technology, but also specific competitive processes, as well as mastering of commercial manufacture of high-efficiency and reliable lasers with a good quality of radiation, based on both traditional and new designs. The latter include Nd:YAG lasers with radiation transmitted via optical fibres, the diode-excited lasers in particular [2], and high-power diode lasers with radiation also transmitted via optical fibres [3]. This allows a flexible process fixture to be built, e.g. a Cartesian or anthropomorphous robot, or a focusing head to be used as a hand tool.

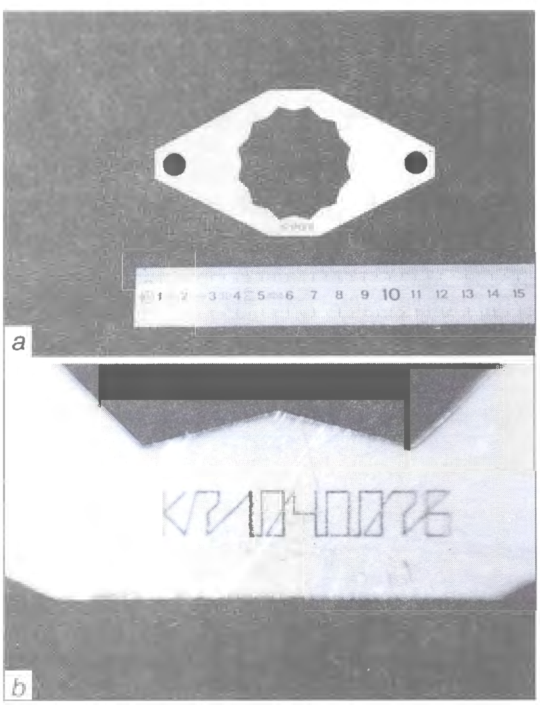

Figure 1. Part made by laser cutting (*a*) with marking (*b*)

Thermal laser technologies are being introduced now into the industry of Ukraine, although at an insufficient rate. The purpose of this article is, firstly, to draw attention of industry to possible solutions TLT can offer to technological problems and, secondly, to give an idea of where investments could hold promise in the case of changing a profile or widening a range of products of an enterprise.

Laser cutting laser cutting of sheet metallic and non-metallic materials has received the widest acceptance in industry. It provides a cutting speed of more than 10 m/min at a steel sheet thickness of up to 15–20 mm, an excellent cut finish for thin (up to 5 mm) sheets and satisfactory cut finish for thick plates. The use of laser cutting is indicated for manufacture of small series of parts or fulfilment of rush orders, where fabrication of a blanking die is not justifiable from the economical standpoint or from the standpoint of time consumption. Modern laser cutting machines are equipped with computer control systems, this enabling a fast change of the program of a technological process for cutting individual parts. These properties of laser cutting equipment correspond in the best way possible to current requirements of industry of Ukraine (i.e. small-series production, short terms from the moment of making a contract for delivery of equipment to its delivery to a customer).

At present several laser cutting systems are in operation at a number of Ukrainian enterprises: OJSC «Zavod Bolshevik» (Kyiv), YuTZ «Zorya» (Mykolaiv), Concern «Lan» (Aleksandriya, Kirovograd district), etc. Figure 1 shows a sample of a part made by laser cutting at YuTZ «Zorya». The parts shown in the Figure were not just cut out, but marked as well. This was done using the same system and the same machine.

Laser welding can be used to make butt, overlap, T- and fillet welds. Laser welding can be performed with or without filler metal, and with a gas or flux shielding. Laser welding is extensively used in motor industry for manufacture of bodies of cars, joining of transmission gear components, etc. However, laser welding received the widest acceptance in manufacture of tailored blanks for further forming and deep drawing of car components, such as parts of bodies, frames, etc. [4]. Welded tailored blanks will find with time a wide application in agricultural machine building, motor industry and other industries of Ukraine. Therefore, arrangement of manufacture of tailored blanks at our metallurgical plants holds high promise, and this production can be competitive in the external market.

The trend now in aerospace and ship building industries is to replacement of solid metal sheets or parts made from them, ensuring the required structural strength, by welded stringer or multilayer 3D-panels. Laser welding, being characterized by narrow and deep penetration, perfectly suits these purposes. A fragment of the multilayer 3D-panel made by the E.O. Paton Electric Welding Institute is shown in Figure 2. Steel rolling plants of Ukraine are capable of manufacturing such panels by orders of customers.

Modern farms now need milk refrigerators, in which the bottom of a vessel serves as an evaporator of the refrigerating machine. The above vessels are made from two or three sheets hermetically welded on the ends and in the field by spots with a diameter of 10–12 mm, located following a certain pattern to ensure the required strength. Evaporators can be made by arc or resistance welding. This, however, leads to deterioration of their internal surface, which should be smooth and have no open porosity and no folds. Therefore, after welding the internal surface of the vessel should be thoroughly polished, which is a labour-consuming operation. Laser welding presents an easy solution to this problem. The external sheet of the evaporator is welded to the internal bottom under such conditions which do not allow its through penetration. Laser welding heat input into the evaporator bottom is minimum, its distortion is insignificant, and because the weld does not penetrate to the internal surface the latter does not require thorough polishing. Leading manufacturers of milk refrigerators (e.g. Swedish companies) widely apply laser welding. They manufacture refrigerator vessels also for food processing, pharmaceutical and chemical industries. Figure 3 shows a fragment of the evaporator bottom made by laser welding at the PWI.

As shown by the world practice, such TLT as cladding, alloying, amorphization and heat treatment are less common than laser welding and cutting. Cladding is used as a rule for repair operations, while heat treatment and alloying are applied primarily for the manufacture of new parts. Powders, wires and strips of various

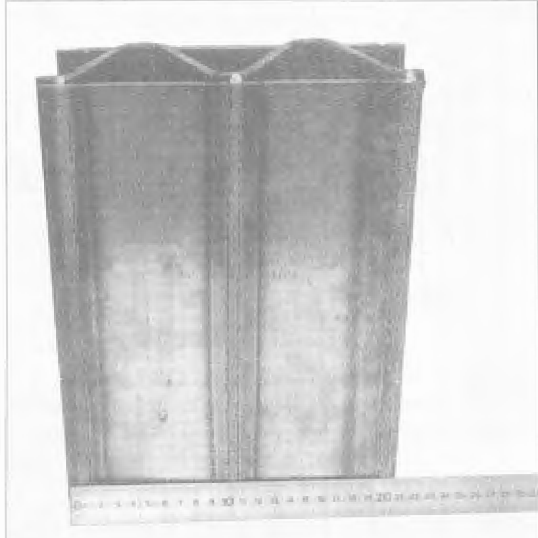

Figure 2. Fragment of a multilayered 3D-panel of sheet low-carbon steel 5 mm thick

metals and alloys are used as filler metals in cladding and alloying [5]. In addition, laser alloying may involve gaseous or liquid media. Heat treatment can be done both with and without surface melting. Special coatings are usually applied to increase absorbing ability of surfaces hardened without melting.

We performed studies aimed at increasing wear resistance of steels and cast irons by laser heat treatment and alloying, and investigations into wear resistance of some alloys deposited by laser cladding. Dry friction tests were conducted by the pin–cylinder method using the friction machine of an ingenious development. Cylindrical samples treated by laser radiation were tested to dry friction at a speed of 1500–2000 m/h under a load of 10–20 MPa. Mating bodies were made from hard steels and alloys (*HRC* 65–55) (Figure 4). The materials of the following chemical composition were used, %: C — 0.38; Cr — 1.0; Ni — 3.0; Mo, V — 0.6 (38KhN3MFA); Ni — 30.0; B, Si — 2.0–4.0; C — 0.8–1.2; Cr — 10.0; Fe – base (PG-N1); B — 1.2–1.8; C — 0.2–0.6; Si — 2.3–2.8; Fe — ≤ 0.1; Ni — base (PG-10N-04); B — 2.5–3.5; C — 0.9–1.8; Si — 2.5–3.5; Cr — 14.0–18.0; Fe — ≤ 3.0; Ni — base (PG-AN6); B — 1.75–2.5; C — 0.3–0.6; Si — 1.25–3.25; Cr — 8.0–14.0; Fe — 1.25–3.25; Ni — base (PG-12N-01).

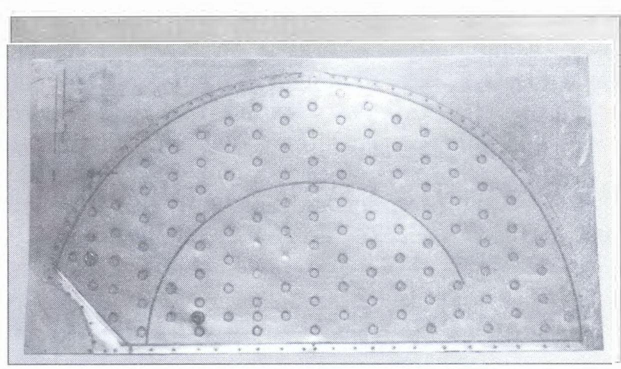

Figure 3. Fragment of the stainless steel evaporator bottom of milk refrigerator with a diameter of 1000 mm and thickness of 2 mm, the built-up sheet being 1 mm thick

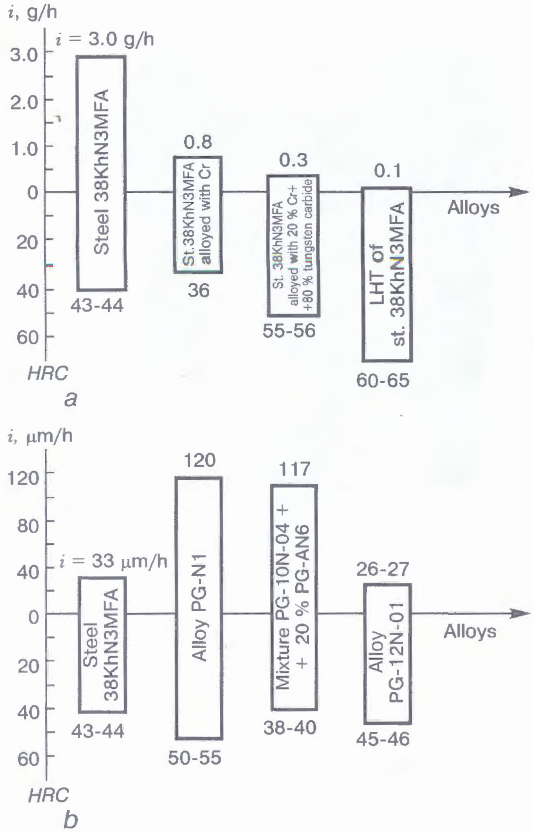

Figure 4. Results of dry friction–wear tests (i) of samples of hypoeutectoid multicomponent steel by the pin–cylinder method at a friction speed of 1650 m/h and specific load of 10–15 MPa: *a* — after hardening by laser alloying and heat treatment; *b* — after laser cladding

Laser treatment has a rather rare use in our country. For example, it is employed at TPO «V.A. Malyshev Factory» (Kharkiv) for hardening of inside surfaces of internal combustion cylinders for locomotive engines. In the future, laser heat treatment and alloying can be recommended for the manufacture of such commercial parts which require high heat locality for hardening of their working surfaces, and properties of which should be at a high level.

Laser restoration cladding has gained wide acceptance owing to a number of unique properties, such as the possibility to deposit layers 0.1–3.0 mm thick with preset properties, absence of buckling of treated parts, minimum allowance for finish machining, etc. [6]. Cladding systems are available at the PWI, Factory No. 410 GA, companies «Engineering Centre for Laser Technologies», «Verkon» and at other companies which use laser equipment. Laser cladding is employed to recondition parts of cars, railway transport, printing equipment, machine tools, etc. (Figure 5). This is a very promising process for our country, as often it is much simpler and less expensive to repair a part of foreign make equipment than buy a new one.

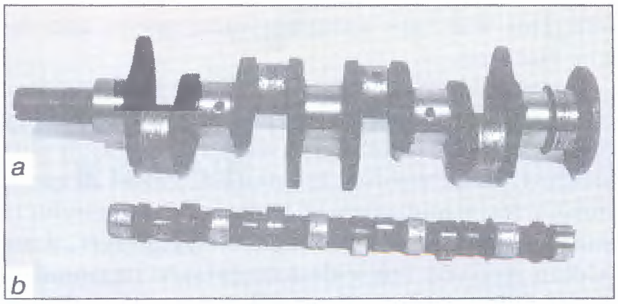

Figure 5. Laser radiation clad crankshaft of «Volga» car with polished main journals (*a*) and transmission of «Renault» car (*b*)

Thermal laser technologies can be widely applied in industry of Ukraine only at a comparatively low price of the equipment involved. Cost of foreign technological lasers and laser technological systems amounts to hundreds of thousands of dollars. As shown by estimation, domestic production of both technological lasers and technological systems for cutting, welding and other types of TLT will be 2–3 times less expensive than the foreign one. There is an R&D potential for their development and arrangement of their mass production. Late in the 1980s–early in the 1990s a CO_2-laser with a power of up to 10 kW [7] and a laser cutting machine «Lazurit-2.5», based on the CO_2-laser with a power of 2.5 kW [8], were built in Ukraine, and coolers for lasers, laser optics, etc. were developed and commercially manufactured. But despite this fact, the above laser equipment available in Ukraine is morally obsolete and requires upgrading. The above-said applies also to the technological instruments based on the CO_2-lasers. As far as the R&D potential for development of high-power solid-state lasers is concerned, our country has not created it as yet.

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LASER WELDING OF ALUMINIUM ALLOYS (REVIEW)

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ABSTRACT

The brief review is presented about weldability of aluminium alloys using a laser radiation. The effect of different factors on the stability of penetration of alloys and formation of joints, being free of any most widely spread defects, such as pores, cracks, oxide inclusions, is shown. The lack of necessary information about the load-carrying capacity of aluminium alloy joints made by the laser welding under the complex conditions of loading is outlined.

Key words: *laser welding, aluminium alloys, penetration depth, reflectivity, energy density, plasma flame, shielding gases, weld pool, pores, cracks*

Aluminium alloys, as structural materials, have a wide range of application in different branches of industry: automobile and instrument industries, ship-building, electrical engineering, etc. By their mechanical characteristics the high-strength aluminium alloys are not inferior to some grades of steel. Moreover, they possess such an important property as a low specific weight, that is especially important in manufacture of sea vessels and air vehicles, as well as different kinds of the rolling stock.

Among all the heat sources, used now for welding aluminium alloys, the laser radiation and electron beam have the highest specific density of energy which is concentrated in the heat spot. Figure 1 shows the levels of energy density of different sources which are used in welding or other processes of heat treatment [1].

Welded joints of aluminium alloys are made using all types of welding, but coming from the economical aspects, which are defined, first of all, by the quality of products, the search for the advanced technologies remains still actual [2, 3].

The laser beam, as a highly-concentrated heat source, has been already used in the above-mentioned branches of industry and a volume of its application is growing constantly as compared with other welding sources.

The laser beam is used widely in such technological processes, as welding, cutting, heat treatment, scribing, piercing, marking on various materials (metals, ceramics, plastics, wood, glass) [2, 4, 5].

The material (sample) being treated plays a large role in interaction (absorption) of a target and laser radiation. The absorption depends, first of all, on the length of a laser radiation wave. Thus, the CO_2-lasers generate radiation of 10.6 μm wave length.

In a solid-state ruby laser, where a ruby is a generating element, having a crystalline lattice Al_2O_3 with three-digit ions Cr^{3+}, implanted into it, the waves of 0.69 μm length are generated. The solid-state lasers on yttrium-aluminium garnet, alloyed with neodymium, i.e. Nd:YAG lasers, generate radiation of 1.06 μm wave length. Depending on these factors the absorption of CO_2-laser radiation by the carbon steel is ≈ 4 % (at room temperature), and for aluminium it is less than 1 %. For the same steel the absorption of Nd:YAG laser radiation is 30 %. In this respect, the relation between the depth of steel penetration and different capacity of radiation of CO_2- and Nd:YAG lasers is very significant (Figure 2).

It follows from this Figure that at equal radiation capacity the depth of penetration of steel using Nd:YAG laser is much higher than that in case of using the CO_2-laser [1]. In fact, many other factors, except absorption, such as thermal-physical characteristics of materials, reflectivity of surface of sample in a solid state or surface of a molten weld pool, initial state of the welded joint surface, its roughness and others, influence the penetrability of the laser beam. In a general form the weldability of the most widely used materials using laser is presented in the Table.

Other types of lasers can be used at different methods of treatment of materials. Thus, at present the lasers on nitrogen, vapours of some materials, free electrons, excimer lasers and others have been developed, but they still have a limited application [6].

At present there is a number of high-power laser sources, such as technological CO_2-lasers, having an output power of radiation from 0.75 up to 25 kW, Nd:YAG lasers of 50–3000 W power. In the laboratory conditions the equipment of up to 40 kW capacity is

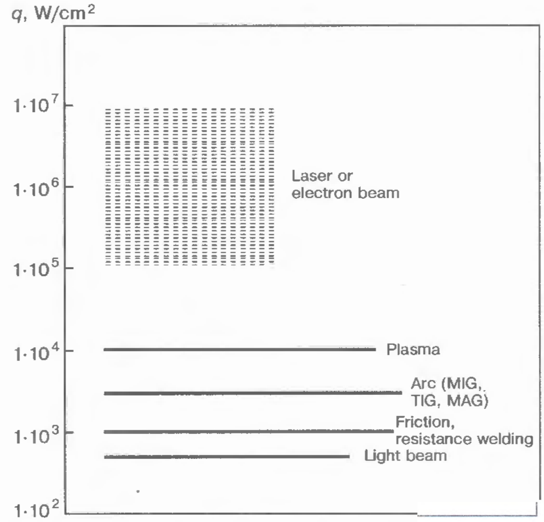

Figure 1. Achievable levels of energy density q at different welding processes

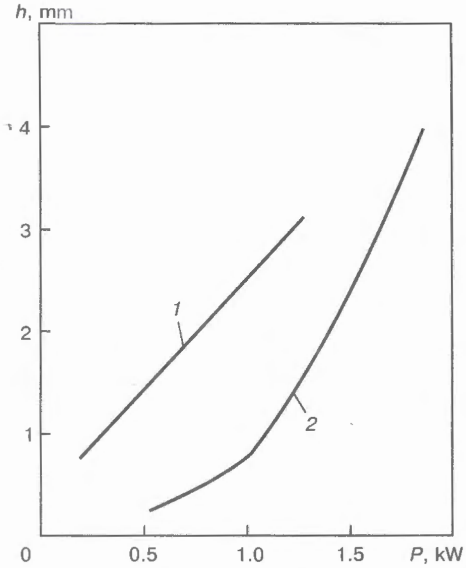

Figure 2. Effect of radiation power *P* in use of Nd:YAG (*1*) and CO_2-laser (*2*) on the depth of penetration *h* of low-carbon steel at 1 m/min welding speed

used. The range of principles of generation of the laser radiation is widening: excimer, argon, semiconductor lasers, lasers on dyes. The project «Eurolaser» can serve as an example of implementation of this field, envisaging the creation of CO_2-laser units of 10–100 kW capacity and excimer lasers of 1–10 kW capacity [4, 7].

Welding of aluminium alloys using the laser beam also finds a wide spreading. The high concentration of the laser radiation and the process flexibility give an opportunity to provide the high efficiency of the process, minimum volume of weld metal, HAZ of small width at the expense of a short-time heat action, saving of the rolled metal, etc. [2, 4]. In addition, the laser beam possesses a number of advantages as compared with the electron beam, namely no vacuum is required, radiation transfer for long distances, feasibility of beam splitting with its supply to several stations simultaneously and fulfilment of complex intricate welds and cuts on large-sized workpieces.

However, when laser is used, certain difficulties are encountered: low efficiency factor of the process, high requirements to the accuracy of edge preparation, expensive equipment, insufficient level of reliability, sometimes, imperfection of the technology [4, 8–10]. With respect to the aluminium alloys, the problems of use of the laser are due, first of all, to the high (about 0.97) reflectivity of liquid and solid aluminium at laser radiation and high fluidity of metal. Often, the aluminium alloys contain such alloying elements as magnesium, zinc, lithium, which are susceptible to intensive evaporation and plasma formation. The problem of a reliable and rational protection of the molten pool against the defects in welded joints is very urgent [4, 5, 9, 11].

Laser-welded aluminium alloys. After development of laser of the power being sufficient for producing welded joints, the attempts were made for welding different aluminium alloys. In 1978 the welding of joints made from alloys 5456 (Al–3 % Mg–Mn alloying system) and 5086 (Al–4.5 % Mg–Mn) was

Weldability of most widely spread materials welded by the laser beam*

Material	*CO_2-laser*	*Nd:YAG laser*
Steel	×××	××
Aluminium alloy	×	××
Copper	×	××
Nickel alloy	××	××
Titanium	××	×××
Zirconium	×	××
Gold and silver	–	×××

*Number of crosses corresponds to the material weldability.

performed. Here, the high weld porosity and, sometimes, substrate flowing out were observed. The conclusion was made about the high sensitivity of aluminium alloys to the intensity of input power and welding disturbances due to high metal fluidity, low melting temperature and high content of easily-volatile alloying components. Taking into account all these peculiarities, joints were performed on alloys 2219 (Al–6 % Cu–Mn) and 5456 (Al–Mg–Mn) with a 9.5 mm butt thickness. In spite of a porosity in joints, the ultimate rupture strength was σ_t = = 342 MPa at σ_t = 345 MPa of the parent metal.

The mechanical properties at the level of the parent metal were obtained in laser welding of alloy 5750-O (Al–3 % Mg), which is used in automobile industry, and Si-containing alloy 6111-T4 (Al–Mg–Mn–Si–Cu) [12]. The welding of sheet metal was performed at high (up to 10 m/min) speeds to prevent the metal overheating at a highly-concentrated heat source. The radiation power was 3 kW. The best results were observed in the range of 5–7 m/min speeds that exceeds by several times the speed which is used in the EBW.

The rather complicated welding of a stringer panel, made from alloy AMg6 (Al–6.2Mg), was performed using laser by the authors of [13]. The panel length was 750 mm, stiffener thickness was 5 mm and the flange thickness was 8 mm. The problems of the panel distortion and internal stresses were solved simultaneously using a special fixture and a highly-concentrated laser source of heating. After tensile tests, the samples showed σ_t = 375 MPa, that corresponds to the parent metal level. The welding was performed at a low speed (30 m/h) for laser. However, the authors stated the feasibility of increasing the process speed. The quality joints without pores and microcracks were obtained on the same alloy at 5 kW laser capacity at the 2 m/min speed [14].

Using laser beam, it is possible to produce high-density welded joints on the aluminium alloys. Welding of vacuum chamber, made from alloy A6063 (Al–Mg–Si), can serve as an example. The laser radiation power was 4 kW, thickness of walls welded was 4 mm and welding speed was 3 m/min. After welding, the welds, which were tested using the method of a helium sample, proved the leakage level $1.33 \cdot 10^{-10}$ Pa·m^3/s. This density of welds makes it possible to provide the ultrahigh vacuum of $1 \cdot 10^{-7}$–$1 \cdot 10^{-10}$ Pa [15].

Many works are devoted to the application of the hybrid methods of welding of aluminium alloys, namely the laser beam with arc [11, 16, 17] or CO_2-laser with Nd:YAG laser [18, 19]. The similar hybrids make it possible to use simultaneously the technological advantages of both methods and to compensate the drawbacks of each of them. This improves the quality of joints and increases the penetration.

The aim of investigations, whose results are described in [17] was to study the feasibility of combination of the CO_2-laser with TIG or MIG processes. During experiments, made on samples from alloys A5083 (Al–4.5 % Mg–Mn) and A6061 (Al–Mg–Si), penetration was increased by 2 mm when the laser of 10 kW power and arc current of 190–210 (for TIG) and 350 A (for MIG) were used. The most quality formation of welds was observed at the combination of laser with a MIG process. Here, the depth of penetration as compared with a laser welding was increased, there were no pores, typical of MIG process and no cracks occurring in welding with the laser only. The combination of CO_2-laser of 4 kW capacity with Nd:YAG laser of 200 W capacity could also improve the weld formation and prevent defects in the joints [9]. The Nd:YAG lasers are used for welding aluminium alloys of small thicknesses, up to 1 mm and higher [2, 20]. This is due to the use of technological lasers of low power for the present, though these lasers for the instrument industry are indispensable, because of a highly-concentrated heating and precision of the process. The air-tight welds are obtained in microinstruments made from the Al–Mg alloys [21]. For the same purpose the welding was performed on products from alloys A5052 (Al–3 % Mg) and A5083 (Al–4 % Mg). The laser power in this case was 1.5 kW, wall thickness was 1 mm and welding speed was 0.6 m/min [22]. The Nd:YAG lasers are used widely in industry and for producing spot welded joints [3, 20].

Technological aspects of improving the efficiency of laser welding of aluminium alloys. *Reflectivity overcoming.* The surface of the pure aluminium in solid and liquid states has a high reflectivity of the laser radiation. The reflectivity factor is about 0.97 for the radiation of an infrared spectrum, while it is somewhat lower for the laser radiation of a ultraviolet region of the spectrum [2]. Thus, the problem requires the solution both at the initial phase of the process when the metal is still in a solid state and also at the stage of the molten pool. The effect of a «threshold power» is associated with a reflection of the laser radiation from the metal solid surface, i.e. at power density, which is lower than a definite value, the metal melting does not occur [14].

This problem is solved in several directions. The first direction refers to the development and application of light-absorbing coatings which should provide the increase in absoption of radiation power and have, at the same time, a minimum effect on the joint quality. The excellent absorber of the laser radiation is the aluminium oxide Al_2O_3. However, under the action of such highly-concentrated heat source, as a laser beam, Al_2O_3 is destroyed not completely, being a cause of formation of defects of inclusions type [16].

To increase the coefficient of absorption it is possible to use different coatings, such as graphite, cement, phosphate coatings, mixtures of oxides, etc. [16, 23, 24]. The results of investigations, described in these works, prove a low effectiveness in use of the graphite which is burnt in air at temperature 600 °C with the formation of CO_2, and at high temperatures it is ionized. Among the coatings investigated the phosphate films (zinc and manganese phosphates) possess the best absorptivity. Mixtures of oxides were also excellent. They provide the low material evaporation, and also the formation of the smaller plasma flame.

The basic moments for producing the quality (thin, dense and smooth) surface of the coating are the dispersity of powder (the finer grain, the higher absorption) and maintenance of proportions of coating components (binder, solvent, mixture of oxides). All these requirements, specified to the coatings, become more strict in the presence of harmful vapours of phosphates. The light-absorbing coatings are useful at the initial stage of their deposition, and they become low-effective with the formation of a molten surface. The preliminary investigations, carried out at the E.O. Paton Electric Welding Institute, showed the rational use of light-absorbing components in the composition of fluxes, as the pool protection is provided and the penetration is increased.

The problem of initiation of the metal surface is also solved by its roughing using abrasives of different grain sizes or a metallic brush [2, 6, 22]. It was stated that when the more rough surface is used, its absorptivity is higher. However, this surface preparation is not much effective due to appearance of a large number of defects in the weld. After formation of the molten pool the effect from its action is lost.

At the stage of the molten pool the different factors may show their effect: welding speed, laser radiation power, scanning, shielding gas, atmosphere composition and the use of a filler. In case of welding of samples, coated with non-metallic materials at a high welding speed, the absorptivity of the surface is increased from 20 to 100 % [16], and with increase in power (at a certain its value) a cavity of penetration is formed and the level of radiation absorption is increased at the expense of an inner reflection of the beam [2, 16]. The use of the filler material also contributes to the increase in absorption and appearance of the cavity [25].

The superposition of actions of auxiliary temperature sources is one more means of increasing the level of the absorbing radiation and the depth of penetration [17]. The combination of CO_2-laser and a low-amperage arc provides a quality welding of samples of small and medium thicknesses. The similar action is shown by a pulsed Nd:YAG laser. To improve the adsorption a deep edge grooving can be used at which a multiple re-reflection of radiation is occurred [26, 27].

Losses in plasma and methods of its elimination. With increase in laser beam power a channel in the form of a cavity is formed. At the same time, the losses for heat conductivity and convection are decreased significantly and the losses for evaporation are increased by many times. They can amount up to 90 % [28, 29]. The intensive evolution of metal vapours leads to the formation of a plasma flame which can exist in several states, such as erosion flame, being transparent for laser radiation and, thus, being not an obstacle; near-surface discharge in metal vapours which absorbs a part of radiation in a close vicinity of the metal surface and, in some cases, can lead to the increase in rates of metal heating [30, 31]; laser wave of absorption which occurs in a surrounding gas and can be a serious obstacle on the path of the beam.

The beam passing through the laser wave of absorption is accompanied by increase in a focusing spot and reduction in power density in the heating spot. The threshold of formation of the laser wave of absorption is estimated by the energy density of $2{\cdot}10^6$ W/cm^2. In [32] the problem of the plasma flame occurrence was also considered. The states of plasma were studied by spectra of radiation, which made it possible to establish that the erosion flame consists mainly of molecular vapours. When analyzing the metal vapours the lines of atoms and ions of the material are recorded. It follows from [30], that this phase corresponds to the state of the near-surface plasma. Breakdown of gas surrounding the target (laser wave of absorption) is accompanied by the more intensive glow of the lines of the gas ions. The threshold of the breakdown appearance is estimated by the density in the range of 0.5–10 MW/cm^2.

The investigation of the plasma flame [33] makes it possible to distinguish two typical frequency ranges: 1–10 kHz, including phases of the erosion flame and near-surface discharge; 100–500 kHz, including high-frequency flame corresponding to the laser wave of absorption. It is stated in all the works that the erosion flame does not cause any difficulties in interaction of the laser radiation with the metal.

The near-surface plasma can contribute both to the faster metal heating and also prevent the appearance of the penetration cavity. In this case the degree of ionizing of vapours of metal and shielding gas is important. The use of helium as a shielding gas promotes the deeper, as compared to argon, penetration because of a high potential of ionizing (i_{He} = 24.580, i_{Ar} = 15.755 eV) [31, 34]. To avoid screening by the near-surface plasma, the authors [31] suggest to use the powerful coaxial jet of the shielding gas instead of a lateral jet. This scheme of the protection will contribute to the moving of the near-surface plasma inside the cavity, and, thus, to the higher penetration (a typical barrel-shaped form of penetration is created).

Another method of prevention of formation of the near-surface plasma is based on its removal from the zone of the beam action [35, 36]. For this purpose, special blowing-out nozzles are used, whose effectiveness depends on their shape, diameter, scheme of arrangement, number, as well as pressure of the blowing-out gas [14]. All the schemes suggested showed a positive effect, however, the high gas consumption (up to 90 l/min) is a main drawback of the above-mentioned method. The results of investigations carried out in [32] indicate that the exhaustion of overheated metal vapours from the penetration cavity occurs always normal to the target surface. Using this feature, it is possible to avoid partially the screening action of the plasma by arrangement of the sample in the inclined position relative to the beam axis in the direction of welding [12, 32, 37]. The angle of inclination of the sample welded should be from 5 to 20°.

The welding speed also affects greatly the nature of the beam interaction with a plasma «cloud». Experiments on study of the plasma state [30] were carried out at 10 cm/s welding speed. The authors state that at the sufficient level of power the time of the channel formation is less than 5 μs; and from the data of [28] the period of the highest losses in plasma begins after 6 μs. This proves that at high speeds of the process the decrease in plasma effect is possible at a negligible decrease in the penetration depth. Thus, the best results were obtained in welding aluminium alloys at the 5–7 m/min speed [12].

Scanning as a method of producing the deep penetration is used successfully and for a long time in the EBW. Taking into account that the laser and electron beams are much similar by the nature of action on the metal as highly-concentrated heat sources, then it is possible to assume that the scanning by the laser beam should also provide the positive results. The problem of realizing effective scanning conditions consists in difficulty of the laser beam control. The laser optics can provide only mechanical scanning that limits significantly the frequency of the beam movement, as compared with an electron beam, but it cannot realize the mechanism of a discrete scanning. Nevertheless, the results of experiments on scanning with a laser beam using accessible conditions are given in [38]. The beam scanning along and across the weld at 2.7 kW beam power did not give the remarkable results. In the best case, the penetration depth remained at the level of penetration at a static beam. It was noted, that the sinusoidal scanning of the trajectory of scanning gives better results as compared with the square scanning. The absence of effect is, probably, due to the insufficient level of the power density. Work [2] contains information about the application of scanning along the beam focusing. Here, the increase in penetration depth by 45 % was noted.

The use of elements that hinder ionizing can be one of the effective methods of the plasma suppression, because, after entering the region of the beam action, they will reduce the screening action of the plasma flame [2]. As regards to the aluminium alloys, this method of addition of this kind of elements into the coating composition is very actual, because such elements as potassium, sodium (with a low potential ionization) or fluorine, chlorine (deionizers) are included into the composition of fluxes for aluminium welding using arc methods.

As alternative, it is possible to use an evacuation [9, 16]. From one side, the advantages of the laser beam as compared with an electron beam are lost, while from another side even a low degree of a vacuum makes it possible to increase the penetration by 3–5 times [9]. Moreover, the specifics of the laser beam enables it to be transferred through the transparent barriers, that can be used for manufacture of special products. After certain improvement of the equipment the laser beam can be used under the space conditions as a welding tool.

In all the works of [29, 30, 32, 33], in which the phases of plasma appearance were studied, the probability of optical breakdown of the gas atmosphere, occurring at some distance from the target surface, was noted, that is a serious obstacle on the path of the laser beam. The need in selecting conditions for prevention of the optical breakdown occurrence is also indicated.

Protection of the weld pool metal. The gas protection using helium or argon is used as a main means for protection of the aluminium alloys in laser welding. Due to a lower potential of ionizing the argon contributes greatly to the formation of a screening plasma. In this connection, the helium is assumed to be more suitable [2, 15, 37]. For saving the expensive helium the use of helium-argon mixtures is possible with a mass share of helium up to 40 %. Here, the depth of penetration remains the same as in use of the pure helium [39]. In [11] the helium is recommended for the flame suppression, while the argon can be used for a common protection of the molten pool.

The effectiveness of protection and degree of use of the beam power depend not only on the selection of the gas, but also on the scheme of its supply. At the arrangement of a nozzle, supplying shielding gas, parallel to the sample surface the reliable protection will not be provided. Therefore, the optimum angles of inclination of the shielding gas nozzle, i.e. 30–40°, were determined experimentally [2, 16, 40]. The parameters which have a direct effect on the quality of protection are a nozzle diameter, distance from the nozzle tip to the surface, gas pressure, supplied to the zone of protection. The evacuation can also be regarded as one of the variants of the possible protection [15].

The use of fluxes as shielding means is not almost mentioned in literature, except the use of fluxes for braze welding of microcircuits. At the PWI a feasibility of use of fluxes for shielding the aluminium alloys in laser welding was studied. Fluxes used for non-consumable electrode welding were selected as basic. The results of studies prove the possibility of using fluxes of a chloride-fluoride type for producing quality butt and overlap spot joints. Graphite, a light-absorbing component, was added in different proportions to the composition of fluxes for the effective use of the power.

Defects of welded joints. The geometric defects or shape defects, such as excessive deformation, poor weld formation, metal leakage, undercuts, caused either by unproper conditions (energy input, focusing, consumption of shielding gas), or by non-quality butt preparation for welding (non-rational profile, contamination, error in butt assembly for welding, etc.) [41].

The inner defects (flaws): pores, cracks, lack of fusion, cavities, inclusions, microsegregation, are mainly connected with the properties of material and its sensitivity to the action of the laser radiation. The properties of aluminium and aluminium alloys, which specify the weld metal susceptibility to defects in welding are as follows: low temperature of boiling, high heat conductivity, reflectivity of solid and molten surface of metal, content of hydrogen in prefabrications, and also the presence of easily-volatile components in the composition of the alloys [41].

Pores. Pores are the most typical defect for the laser welding of aluminium alloys. Usually, they are caused by hydrogen which is contained in metal or enters there together with a moisture. The source of moisture in the zone of a thermal action of the beam can be an oxide film, containing moisture in discontinuities. In alloys, which contain magnesium, the complex oxide film is especially sensitive to hydration. Moreover, the magnesium also contributes to more complete dissolution of hydrogen [2, 42]. After entering the molten metal, hydrogen is evolved in the form of bubbles at the phase of cooling during decrease of its dissolution in the metal welded. Except hydrogen other gases can be a cause of pore formation, for example, nitrogen from atmosphere, because of a poor protection of the pool molten metal. The shielding gases, helium and argon, can form pores or voids at their enter the molten metal as a result of an intensive stirring of the pool metal and collapsing of the penetration channel. By the degree of effect of shielding gases on the pore formation they can be arranged in the following sequence, %: hydrogen — 90; nitrogen — 5; helium and argon — 5 [42].

The main method of pore prevention in case of use of the Nd:YAG laser is the rational formation of the welding pulse. The pulse shape modulation makes it possible to ensure the most favourable conditions for producing the required penetration and, simultaneously, for the metal cooling. The time modulation can control the period of metal duration in the overheated and molten state that reduces to minimum the probability of initiation of defects [42, 43].

In case of CO_2-laser with a constant generation of radiation the causes of the pore formation are the same, however, the approach to their prevention is different. Here, a welding speed has a special effect. With its increase the time of pool metal contact with atmosphere is decreased [11]. This effect of «high welding speed» can cause a contrary result. Analysis of causes of porosity in aluminium alloys showed that in Mg-free alloys the porosity, due to the dissolved hydrogen, was highest, while in the Mg-containing alloys it was minimum [42]. This situation is quite opposite to the results obtained in use of the Nd:YAG laser. The mentioned effect is explained by the fact that magnesium contributes to the more complete dissolution of hydrogen, but at high welding speeds typical of CO_2-lasers, the hydrogen has no time to be accumulated into bubbles and to evolve, because of the fast proceeding of the process. The results of experiments made on samples of alloys 5754 (Al–Mg) and 6111 show that the pore-free welded joints can be produced at the speeds of about 7 m/min [12].

The evaluation of effect of pore sizes on strength characteristics [44] of aluminium alloy welded joints made by using laser showed that, if the air-tightness requirements are not specified to the joint, then the pores of small sizes are quite admissible, as they are not essential stress raisers.

The general technological measures for prevention of porosity may include a reliable protection of the pool molten metal with inert gases, as well as the removal of contaminations from the sample surface by etching, oxide film — by scraping or other methods before welding [2, 3, 16].

Cracks. The heat-hardened aluminium alloys and alloys, which contain elements, forming the fusible eutectics of Al–Mg and Al–Si types, are most susceptible to the crack initiation. The high speeds of welding also contribute to the decrease in crack-resistance of welds, as in this case the effect of the highly-concentrated heat source promotes the occurrence of a rigid thermal cycle and, respectively, high rates of cooling. This narrows the range of possible conditions and their selection is complicated by a search for a compromise between the high speed, providing the pore suppression in the weld, and an acceptable thermal cycle, not causing the crack initiation. This problem refers mainly to the CO_2-laser welding. The authors of [25] recommend to use a filler material for these purposes which will make it possible to avoid the overheating of the sample welded. The scanning of the laser beam along the focus can be used as a method of crack prevention [2], as it contributes to the more effective heat input and decrease in energy input. The use of the tandem welding with two beams [26], combination of beam of the CO_2-laser with an arc or a beam of the Nd:YAG laser decreases the crack formation [15, 17]. In particular, the authors of [17] combined CO_2-laser of 10 kW capacity with TIG and MIG processes and prevented the crack initiation, which initiated inevitably in the aluminium alloy 6061 during welding using only a laser beam. The depth of penetration was also increased here.

Fillers with special properties can also be used as a means of crack prevention. Titanium or nickel interlayers were used in sealing of the instrument bodies made from the aluminium alloys. Titanium and nickel possess the higher absorptivity than that of aluminium, and create conditions for «curing» of a molten aluminium constituent of hot cracks between the high-temperature phases on the base of titanium or nickel [18, 21].

Losses of alloying elements. The laser beam, as a highly-concentrated heat source, evaporates intensively the pool metal. Therefore, the elements, having the low temperature of boiling, are evaporated more intensively. Magnesium, zinc and lithium belong first of all to the above-mentioned elements in the composition of the aluminium alloys. In magnesium alloys 5052 (2.5 % Mg) and 5083 (4.5 % Mg) the losses were 0.48 and 0.74 %, respectively, at 1.5 kW beam power and 0.6 m/min welding speed [22]. The maximum losses are observed in the zone of the highest overheating, i.e. mainly in the upper and middle part of the melting zone. It was noted that the larger magnesium content in the alloy composition, the higher its losses in evaporation. This aspect, as regards to the lithium alloys, is not elucidated in literature.

The increase in the welding speed is the reliable method of decreasing losses of alloying elements. As the authors of [12] recommend, its increase should be up to 10 m/min. Using this approach, they managed to reduce the losses of magnesium in alloy 5754 from 3.0 to 0.2 %. For comparison, in EBW the magnesium losses in alloy AMg6 may exceed 1 % and the same amount of zinc in alloy V95 (Al–Zn–Mg–Cu). In arc methods of welding these losses are up to 3–6 % [3].

Quality control of joints. In many works related to the quality of the laser welding joints the aspect of in-process control of the selected parameters of the process is considered. This approach is, first of all, connected with a high efficiency of the laser welding which is used, as a rule, in the conditions of a conveyor production where any change in process parameters can cause the repetition of defects and rejection of a large batch of products because of the high speed of the process.

During recently, the plasma formed in metal vapours, is used more often as an object of the in-process control. Plasma fluctuations are used for judgement about the violations of the normal process [45–48]. Plasma monitoring is made by different methods. The plasma control using the light diodes can evaluate the presence or absence of a complete penetration in butt welding or the same parameter for the upper sheet in case of the overlap welding [45], i.e. to control the main parameter during the process. The spectrometric method can control the wider range of parameters: to estimate the plasma temperature (to control the process phases and, when necessary, to perform the plasma control), to indicate the presence of contaminations, to control the losses of elements [46]. For the Al–Mg alloys the control can be made by the atomic lines of spectrum of aluminium, magnesium, copper, zinc and iron or molecular MgO, AlO, AlH with the help of which it is possible to evaluate the effect of shielding atmosphere and completeness of proceeding of different reactions at different stages of the process.

Specially-designed equipment on the basis of spectrometry method and measurements of electron temperature provides a feasibility to reveal such defects, as a lack of fusion of edges, blowholes, splashes, defects of assembly (steps) in a real time, approximately one month [47].

Using the method of a thermovision observation it is possible to study directly and evaluate the deviation from the preset process parameters in different shielding media (in argon, helium) and at different their pressures [48].

As an alternative to the thermoelectron observation of the plasma, the authors of [49] used the method of acoustic monitoring of the zone of the beam–metal interaction. The comparison of acoustic (in the range of audibility) and ultrasonic method using the expensive highly-sensitive microphones showed the advantage of the acoustic method as the cheapest method. The similar procedure can reveal reliably the deviations in focus and width of gap in the butt.

The express evaluation of the penetration depth, except plasma control, can be made using the infrared sensors, as was suggested in [50]. The observation is made by measurement of temperature of the reverse side of the product.

CONCLUSIONS

1. The laser welding finds more and more wide spreading, in particular in manufacture of elements and structures of mass production, for example, of body elements of the motor cars.

2. The additional integrated investigations for improvement of technology and technique of welding are still required for a wide implementation of the laser welding in structures made from the high-strength aluminium alloys, including their modern varieties, such as Al–Li alloys.

3. In the conditions of a practical realization of the laser welding process, the solution of the problems of prevention of formation of the plasma flame from the penetration channel, improvement of stability of existence of the penetration channel, reduction of the level of defects in weld metal and ensurance of the reliable protection of the weld pool both from the side of the laser beam and also from the reverse side of the weld remains still complicated.

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LASER-MIG PROCESS FOR AUTOMOTIVE INDUSTRY

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ABSTRACT

Considered is a separate and combined effect of laser and arc radiation sources in welding of materials. In the latter cases it is possible to achieve a positive synergic effect, ensuring a simultaneous improvement in quality of joints and high productivity of the welding process at relatively low costs.

Key words: *laser welding, arc MIG welding, hybrid process, synergic effect, quality of welding, productivity, costs*

It has been known how to combine laser light and the arc into an amalgamated process of welding thin materials ever since the 1970s, but for a long time thereafter, no further development work was undertaken. Recently, researchers have turned their attention to this topic again and attempted to unite the advantages of the arc with those of the laser in a hybrid welding process. Whereas in the early days laser sources still had to prove their suitability for industrial use, nowadays they are standard technological equipment at many manufacturing enterprises. The combination of laser welding with another welding process is referred to as a «hybrid welding process». This means that a laser beam and an arc act simultaneously in one welding zone, and influence and support one another.

Laser welding requires not only high laser power but also a high-quality beam in order to obtain the desired «deep-weld effect». The resulting higher quality of the beam can be exploited to obtain either a smaller focus diameter or a larger focal distance.

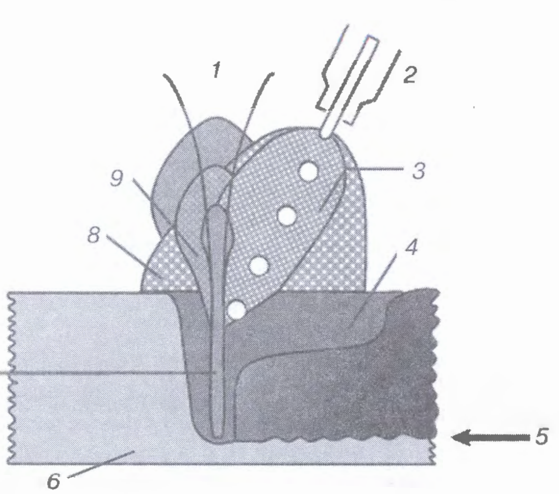

Figure 1. Schematic representation of the laser-MIG welding process: *1* — laser beam; *2* — arc electrode; *3* — arc; *4* — fusion zone; *5* — welding direction; *6* — workpiece; *7* — vapour cavity; *8* — plasma; *9* — laser-induced metal vapour

For the development projects that are currently underway at Fronius International, a lamp-pumped solid-state laser with a laser beam power of 4 kW is being used. The laser light is transmitted via a 600 μm glass fibre. The laser light is transmitted via a glass fibre, in which the beginning and the end are water-cooled. The laser beam is projected onto a workpiece by a focusing module with a focal distance of 200 mm.

For welding metallic workpieces, the Nd:YAG laser beam is focused at intensities of above 106 W/cm^2. When the laser beam hits the surface of the material, it heats up this spot to vaporization temperature, and a vapour cavity is formed in the weld metal due to the escaping metal vapour. The distinguishing feature of the weld bead is its high depth-to-width ratio. The energy flow density of the freely burning arc is slightly above 104 W/cm^2, which does not allow welding with deep penetration.

Figure 1 illustrates the basic principle of hybrid welding. The laser beam depicted here feeds heat to the weld metal in the top part of the bead, in addition to the heat from the arc. Unlike a sequential configuration where two separate welding processes act in succession, hybrid welding may be viewed as a combination of both welding processes acting simultaneously in one and the same process zone. Depending on which arc or laser process is used, and on the process parameters, the processes will influence one another to a different extent and in different ways [1, 2].

Thanks to the combination of the laser process and the arc process, there is also an increase in both the weld penetration depth and the welding speed (as compared to either of the processes used on its own). The metal vapour escaping from the vapour cavity retro-acts upon the arc plasma. Absorption of the Nd:YAG laser radiation in the processing plasma remains negligible. Depending on what ratio of the two power inputs is chosen, the character of the overall process may be determined to a greater or smaller degree either by the laser or by the arc [3, 4].

Absorption of the laser radiation is substantially influenced by the temperature of the workpiece surface. Before the laser welding process can get underway, the initial reflectance must first be overcome,

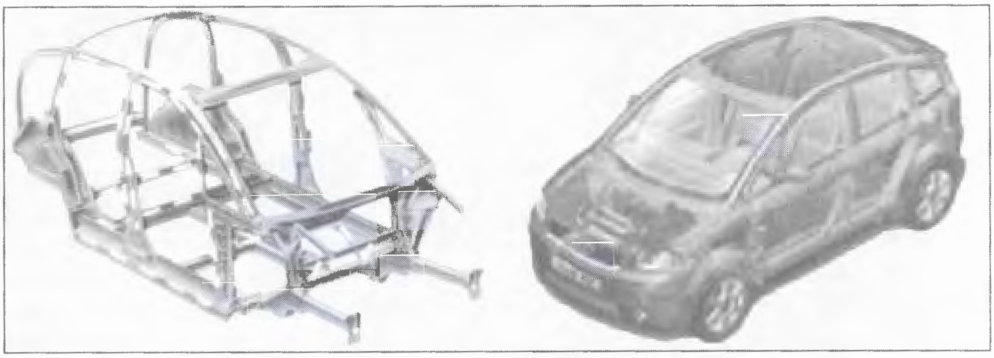

Figure 2. «Audi-A2» space frame

especially on aluminium surfaces. This can be achieved by starting welding with a special start program. After the vaporisation temperature has been reached, the vapour cavity is formed, with the result that nearly all the radiation energy can be input into the workpiece. The energy required for this is thus determined by the temperature-dependent absorption and by the amount of energy lost by conduction into the rest of the workpiece. In laser-MIG welding, vaporisation takes place not only from the surface of the workpiece but also from the filler wire, meaning that there is more metal vapour available, which in turn facilitates the input of the laser radiation. This also prevents process dropout .

Laser-MIG welding found a wide application in automotive industry. The «Audi-A2» space frame (Figure 2) consists of 30 m laser (light strips in Figure) and 20 m MIG weld length. Structure of joints on «Audi-A2» is shown in Figure 3. Additionally, 1700 rivets are also used. By using space frame technology, a weight reduction of 43 % is possible in comparison to a steel car body.

Figure 4 shows a laser-MIG welded joint of a AlMg3 cast material with an AlMgSi1 sheet material. The filler wire is AlSi5 and the shielding gas used is argon. With increasing laser power, deeper penetration is possible. Combining the laser beam with the arc in this way achieves a larger weld pool than with the laser beam weld process on its own. This makes it possible to weld components with wider gaps.

In the automotive industry there are many applications of overlap welding without joint preparation. At the moment, the state-of-the-art process for this welding job is the laser welding process with a cold filler wire, due to hot cracking of the aluminium alloy. When the joint is welded with a filler wire, a lot of the laser energy will be lost in order to melt that filler wire.

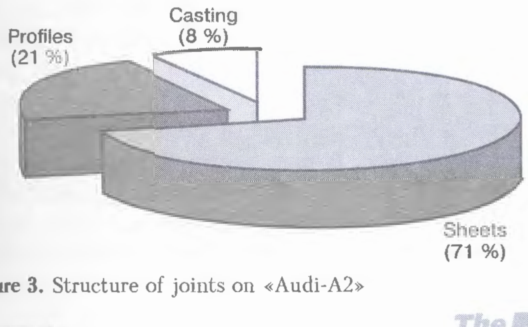

Figure 3. Structure of joints on «Audi-A2»

Figure 5 represents the differences between laser-MIG and laser welding on an overlap joint (gap 1 mm) with a welding speed of 2.4 m/min. In the case of laser welding, there is no possibility to fill up the weld gap, and undercut is produced. Also, there is only a very small penetration into the base material. The weld bead width is very small, and therefore a low tensile strength will be expected. In the case of laser-MIG welding, additional material is transported into the weld pool. The undercut is filled with the wire from the MIG process, and a portion of laser energy is now saved. This saved laser energy can be used to increase the penetration into the base material, and the weld bead width is bigger than the material thickness, which is predicted from the numerical simulation. The welding head should have small geometrical dimensions, so as to ensure good accessibility to the components to be welded, especially in the autobody field. Moreover, it should be designed to permit both a suitable detachable connection to the robot head and adjustability of such process variables as focal distance, and torch stand-off distances in all Cartesian co-ordinates. Figure 6 shows the welding head, while the process is in action.

The spattering that occurs during the welding process leads to increasing dusting of the protective glass. The quartz glass is coated on both sides with an antireflective material and is intended to protect the laser optical system from damage. Depending on the degree of dusting, the spatter accumulating on

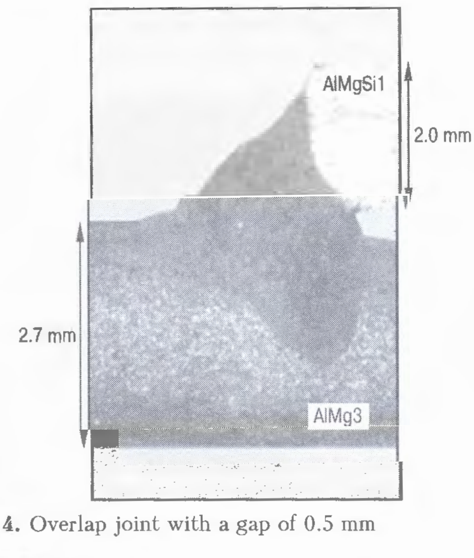

Figure 4. Overlap joint with a gap of 0.5 mm

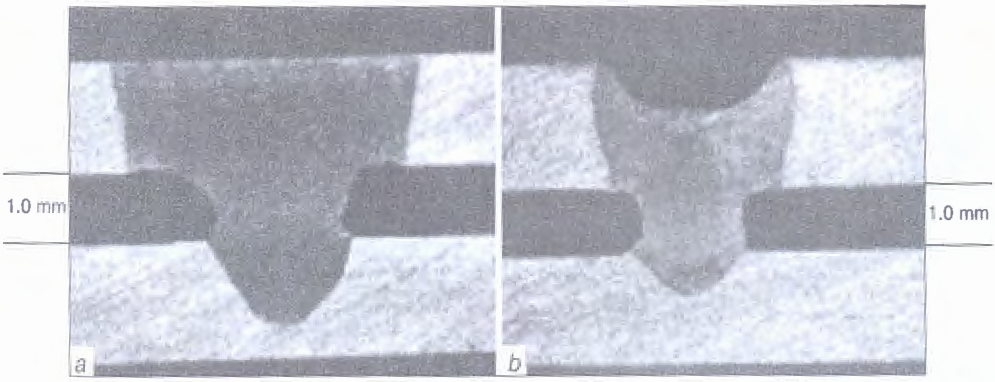

Figure 5. Comparison between laser-MIG (*a*) and laser welding without filler wire (*b*) at a speed of 2.4 m/min

the glass can cause the laser power actually impacting upon the workpiece to decrease by as much as 90 %. Heavier dusting generally leads to the destruction of the protective glass, as such a large proportion of the radiant energy is then absorbed by the glass itself, causing thermal stresses in the glass.

With the laser-MIG welding procedure it is possible to weld materials of aluminium, steels and stainless steels from up to 4 mm material thickness. If the thickness is too large, full penetration is not possible. For joining zinc coated materials, it is also preferable to use the laser brazing process. Further applications in the automotive industry are power trains, axles and car bodies, where the laser hybrid welding process can be suitable.

The following advantages result from the merging of arc and laser beam:

✧ advantages of laser-MIG welding over laser welding:

- higher process stability;
- higher bridgeability;
- deeper penetration;
- greater ductility;
- lower capital investment costs;

✧ advantages of laser-MIG welding over MIG welding:

- higher welding speeds;
- deeper penetration at higher welding speeds;
- lower heat input;
- higher tensile strength;
- narrower welds.

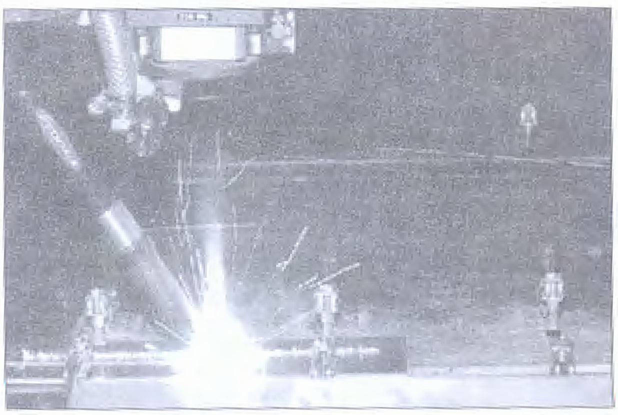

Figure 6. Laser-MIG welding process

The arc welding process is characterised by a low-cost energy source, good bridgeability and by the facility for influencing the structure by adding filler metals. The distinguishing features of the laser beam process, on the other hand, are the great welding depth, high welding speed, low thermal load and narrow weld bead that it achieves. Above a certain beam density, the laser beam produces a «deep-weld effect» in metallic materials, which enables components with a greater wall thickness to be welded, provided that the laser power is sufficiently high. Laser-MIG welding thus makes for higher welding speeds, process stabilisation due to the interaction between the arc and the laser beam, increased thermal efficiency and greater workpiece tolerances. Because the weld pool is smaller than in the MIG process, there is less heat input and thus a smaller HAZ. This means less weldment distortion, which reduces the amount of subsequent post-weld straightening work that needs to be done. Where there are two separate weld pools, the subsequent heat input from the arc means that the laser beam welded area, especially in the case of steel, is given a post-weld tempering treatment, spreading the hardness values more evenly across the joint.

Turning now to the economic advantages of hybrid welding over laser welding, the following statements can be made. The welded joint consists partly of a laser weld and partly of a MIG weld. The hybrid process makes it possible to reduce the power of the laser beam, meaning that the energy consumption of the laser source can be greatly decreased, as the laser beam apparatus has an efficiency of only 3 %. In other words, a reduction of 1 kW in the laser beam power impacting upon the workpiece leads to a reduction of ≈ 35 kW in the power consumed from the electricity mains.

A laser beam apparatus costs around EUR 0.1 mln for each 1 kW of laser beam power. To take just one example, in a case where the utilisation of the hybrid process makes it possible to use a 2 kW laser beam apparatus instead of one with 4 kW of beam power, this results in savings of EUR 0.2 mln in investment outlays. However, it must be remembered here that for the hybrid process, a MIG machine costing around EUR 20,000 will be needed. Thanks to the higher welding speed, both the fabrication time and the welding costs can be reduced.

It should be noted in conclusion that laser-MIG welding is a wholly new technology that offers synergies for wide fields of application in metalworking industries, especially where it is not possible or financially viable to achieve the component tolerances that are required for laser beam welding. The much wider range of application and the high capability of the combined process lead to enhanced competitiveness in terms of reduced investment outlays, shorter fabrication time, lower manufacturing costs and higher productivity.

Basic research studies [5–9] have shown that a process is possible in which, by combining the two processes, synergies can be achieved and the drawbacks of each separate process can be compensated for, resulting in enhanced welding possibilities, weldability and welding reliability for many different materials and constructions. In particular, this has been demonstrated for aluminium alloys.

By choosing favourable process parameters, it is possible to selectively influence weld properties, such as geometry and structural constitution. The arc welding process increases the bridgeability by adding filler metal; it also determines the weld bead width and thus reduces the amount of workpiece preparation that is needed. Moreover, the interactions taking place between the processes lead to a substantial increase in the efficiency of the process. This combination of the processes also requires considerably smaller investment costs than the laser welding process does.

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PECULIARITIES OF PENETRATION OF METAL IN LASER-ARC WELDING USING YAG LASER

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ABSTRACT

Simplified model of thermal processes occurring in metal in combined laser-arc welding performed in the thermal conductivity penetration mode is suggested. The model allows for the effect of contraction of the anode region of the arc as resulting from laser evaporation of metals. Experimental and numerical investigations into peculiarities of penetration of stainless steel samples in combined welding using the YAG laser and the argon arc with a non-consumable electrode were conducted. Results of the calculations are in a sufficiently good agreement with the experimental data.

Key words: *laser-arc welding, electric arc, laser beam, metal penetration, temperature field, investigations*

Along with traditional methods of welding and treatment of metals using arc, laser or electron beam heating, the combined technological processes realized by a simultaneous use of two different heat sources, e.g. laser beam and electric arc [1, 2] receive an increasingly wide acceptance now. One of the main causes of emergence of the combined processes was a trend to combine advantages and eliminate drawbacks characteristic of the known arc and beam technologies taken separately. The initial investigations into the laser-arc methods of welding, cutting and surface treatment showed that they are characterized by a number of peculiarities, which cannot be explained by a simple superposition of properties of each of the above heat sources [3–5]. For example, it was established that the combined laser-arc effect on metals increased the efficiency of both laser and arc powers, improved spatial stabilization of the arc spot on a workpiece surface and raised the degree of contraction of the anode region of the arc discharge.

Issues of experimental investigations into peculiarities of laser-arc welding using CO_2-lasers are covered in voluminous literature (see, e.g., review [6]). At the same time, solving such an important problem as determination of peculiarities of heat impact on a workpiece by the electric arc and laser beam combined in a single process is impossible without a detailed theoretical analysis. The need for such an analysis, as well as the recent trend to replacement of high-power technological CO_2-lasers by simpler and small-sized

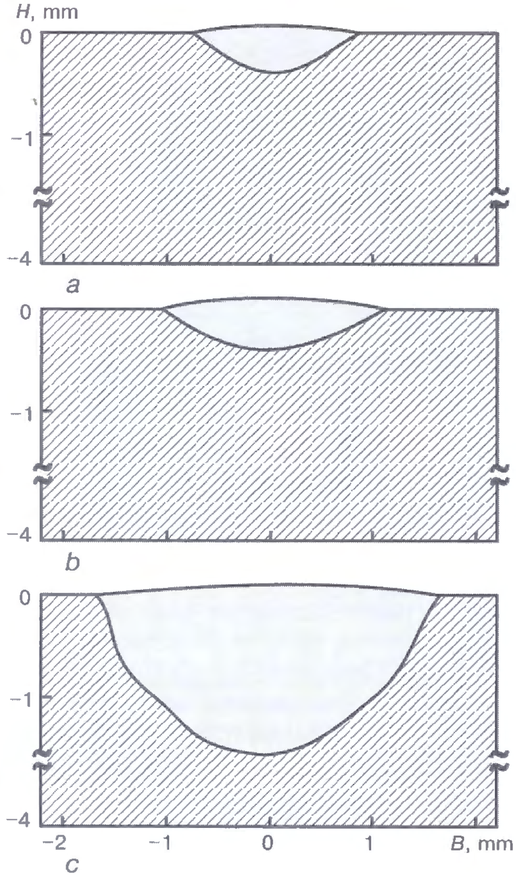

Figure 1. Profiles of the weld beads produced in the experiments on laser (*a*) argon-arc (*b*) and laser-arc (*c*) welding of steel 10Kh18N10T 4 mm thick: $I = 75$ A, $v = 12$ m/h, $Q = 285$ W, $r_F =$ = 0.7 mm (here and in Figures 2–5 *H* and *B* are penetration depth and width, respectively)

solid-state YAG lasers of a lower power, stipulated the purpose of this study, i.e. experimental and theoretical investigations into the thermal-conductivity mode of penetration of metal in welding using a combined laser-arc heat source (beam of a solid-state laser and argon arc with a non-consumable electrode).

Focused radiation of the pulse-periodic YAG laser with a power of $Q \leq 400$ W [7] (radius of the focusing spot $r_F = 0.7$ mm) and the DC ($I = 60$–100 A) argon arc with a tungsten cathode located at an angle of 45° to the metal surface ahead of the laser beam in a direction of welding were used in the experiments. Distances from the electrode tip to the sample surface and to the axis of the laser beam were the same and equal to 2 mm, thickness of the samples was $\delta =$ = 1–4 mm, and material was stainless steel 10Kh18N10T (C — 0.1; Cr — 18.0; Ni — 10.0; Ti — 0.6 wt.%). It was established as a result of the experiments that the cross section area of the weld beads produced by the combined method was much in excess of the sum of the corresponding areas of the welds made separately by the laser and arc methods (at the same values of the arc current, laser beam power and welding speed). An increase in the area occurs mainly due to an increase in the penetration depth (Figure 1).

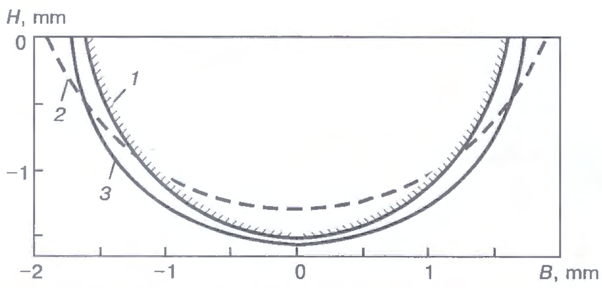

Figure 2. Experimental profile of the weld (*1*) in laser-arc welding of stainless steel 4 mm thick, and calculated shape of isotherm of metal melting using independent heat sources (*2*) and allowing for contraction of the arc in the combined process (*3*)

In addition, it turned out (Figure 2) that the experimental shape of a weld in laser-arc welding did not correspond to the profile of an isotherm of metal melting calculated from the formula for a quasi-stationary temperature field in a flat layer δ thick for two independent, coaxially acting and moving heat sources (laser and arc sources are assumed to have normal circular parameters q_l, r_l, q_a and r_a and be of the surface type, as we consider the thermal conductivity penetration mode). In the Cartesian coordinate system (x, y, z) with axis x directed along movement of the sources, this formula has the following form [8]:

$$T = T_0 + \frac{1}{2\pi\lambda\sqrt{\pi a}} \int_0^\infty \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(z-2n\delta)^2}{4a\omega^2}\right] \times \left\{\frac{q_l}{(\omega^2 + r_l^2/4a)} \exp\left[-\frac{(x+v\omega^2)^2 + y^2}{4a\omega^2 + r_l^2}\right] + \frac{q_a}{(\omega^2 + r_a^2/4a)} \exp\left[-\frac{(x+v\omega^2)^2 + y^2}{4a\omega^2 + r_a^2}\right]\right\} d\omega, \quad (1)$$

where T_0 is the initial temperature of metal (ambient temperature); λ and a are the coefficients of thermal conductivity and diffusivity of metal, respectively; q_l and q_a are the effective powers of the laser and arc heat sources, respectively; r_l and r_a are the characteristic sizes of the respective heat sources determined as a distance from the axis at which the heat flow decreases by a factor of e; v is the welding speed. The following magnitudes of the values included into formula (1) were used for calculation of the isotherm of melting in a case where the sources were independent (Figure 2, dashed curve): $T_0 = 20$ °C, $\lambda =$ = 0.218 W/(cm·K), $a = 0.048$ cm^2/s for steel 10Kh18N10T [9], and $v = 12$ m/h. The effective power of the laser heat source was calculated from formula

$$q_l = \Gamma Q, \quad (2)$$

where Γ is the coefficient of absorption of laser radiation with a wave length of 1.06 μm, characteristic of the YAG lasers (in a case of stainless steel $\Gamma \approx 0.6$ [10]) by the metal surface, and the effective power of the arc source was determined from the plot of dependence of power input into a workpiece in argon-arc welding upon the arc current ($q_a \approx 300$ W at $I = 75$ A [11]). A characteristic size of the laser heat

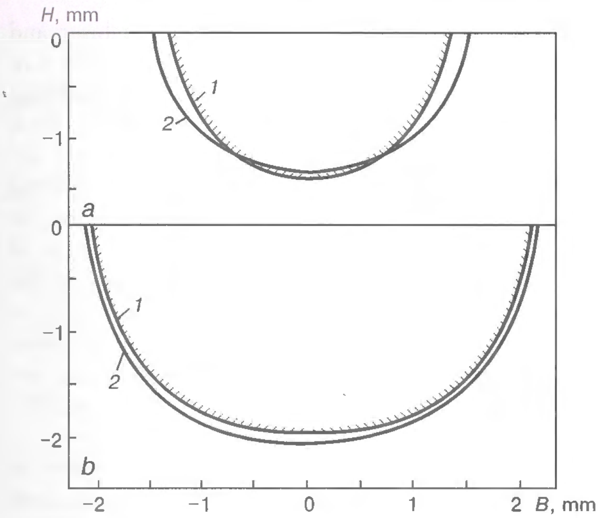

Figure 3. Profiles of the welds produced in the experiments (*1*) on laser-arc welding of stainless steel at an arc current of 60 (*a*) and 100 (*b*) A, and corresponding calculated isotherms of metal melting allowing for contraction of the arc (*2*)

source, r_l, was selected equal to $r_F/2$ and that of the arc heat source, r_a, was determened from a condition of the best fit of the calculated isotherm of melting (at $q_l = 0$ and selected values of q_a and v) to the experimental profile of the weld for argon-arc welding (Figure 1, *b*), which yields $r_a = 1.58$ mm.

The following model was suggested to explain the effect of violation of additivity of thermal effect of laser and arc heat sources using the YAG laser. As plasma of the argon arc column under an atmospheric pressure is almost transparent to radiation with a wave length of 1.06 μm [6], the only mechanism of interaction of the laser beam and the electric arc in a given case is variation in the character of occurrence of the anode processes due to an additional laser heating of the workpiece (anode) surface. Burning of the conventional argon arc at currents of more than 100 A involves an anode spot [12], the formation of which is associated with an intensive evaporation of metal from the anode surface, and the arc is contracted into this spot [13, 14]. In the above experiments on laser-arc welding the lower-current arc was used, which caused no evaporation of metal at the absence of its laser heating (which is confirmed by calculations using formula (1) at $q_l = 0$) and, accordingly, no formation of the anode spot. An extra heat input due to the use of such a concentrated heat source, which the laser beam is, leads to formation of the boiling zone on the sample surface. As a result, the arc starts burning in metal vapours which have a lower ionization potential than argon ($U_{Fe} = 7.9$ and $U_{Ar} = 15.8$ eV). In this case the arc current tends to concentrate within the given zone, which leads to an increase in the density of the power introduced by the electric arc into a workpiece in laser-arc welding. Therefore, formula (1) can be used for a more accurate quantitative estimation of the results of the combined thermal effect on metal welded in the thermal-conductivity penetration mode, supposing the radius of the arc heating spot, R_a (for a normal circular source with $r_a \approx R_a/2$) to be equal to averaged radius r_b of the established zone of metal boiling, and assuming in the first approximation that the effective power of the arc heat source remains unchanged.

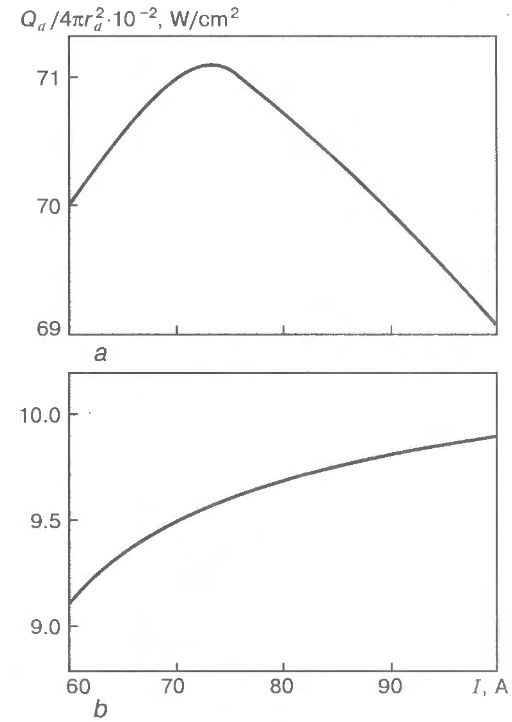

Figure 4. Calculated dependence of density of power input into a workpiece in laser-arc (*a*) and argon-arc (*b*) welding of steel 10Kh18N10T upon the arc current

Profile of the isotherm of metal melting calculated within the frames of this model (allowing for the arc contraction in the combined process) is shown in Figure 2 by a solid curve (all the selected magnitudes of the values included into formula (1) are the same, except r_a, which in this case becomes equal to 0.58 mm). Results of these calculations for laser-arc welding of stainless steel 4 mm thick at the same welding speed and a different value of the arc current are shown in Figure 3. As it follows from comparison of the given calculated curves with profiles of the welds produced experimentally under the corresponding welding conditions, the calculated and experimental data are in a sufficiently good agreement (especially at high arc currents). This confirms validity of the suggested mathematical model for quantitative estimation of thermal effect on metal by the combined laser-arc heat source.

Numerical investigation into peculiarities of thermal effect on a workpiece by the laser beam and electric arc combined in a single process was conducted on the basis of the developed model of metal penetration using the YAG laser. It was established that density of the power introduced into metal by the arc in laser-arc welding was almost 7 times as high as that in argon-arc welding (Figure 4). In addition, the character of dependence of the power density upon the arc current is also changed (see Figure 4). Whereas in argon-arc welding within the investigated range of currents the arc power density monotonously increases

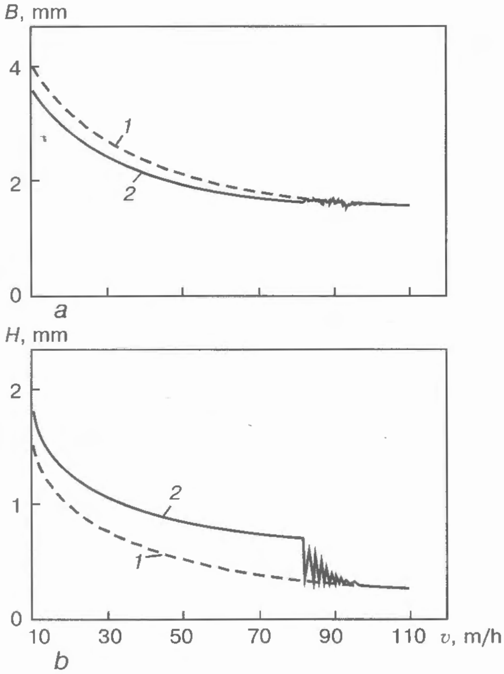

Figure 5. Calculated dependencies of the maximum weld width (a) and penetration depth (b) in laser-arc welding of stainless steel upon the welding speed using independent heat sources (1) and allowing for the arc contraction in the combined process (2)

with an increase in I [11], in combined welding using the laser beam with a power of 285 W it has a maximum at $I \approx 70$ A. This fact should be taken into account in realization of a specific combined process by selecting such an arc current at the preset values of the laser radiation power and welding speed that the density of the power introduced by the arc into the metal welded is maximum.

Calculated dependencies of the maximum weld width B and penetration depth H, shown in Figure 5, indicate that there is a certain range of the combined welding speeds in which the effect of contraction of the anode region of the arc due to laser evaporation of metal is most pronounced. In laser-arc welding of stainless steel 4 mm thick using the argon arc at a current of 75 A and YAG laser beam power of 285 W (r_F = 0.7 mm) this range covers speeds of up to 82 m/h. At welding speeds of above the said value the penetration depth fluctuations begin, which is associated with an unstable evaporation spot existing on the metal surface, this spot fully disappearing at a speed of 97 m/h. As the welding speed is further increased, the laser beam and the electric arc start acting as two independent heat sources (see Figure 5).

Contraction of the anode region of the arc and its stabilization in the zone of laser evaporation of metal in laser-arc welding enable the speed of the combined welding process to be fundamentally increased, as compared with the speed of welding using the conventional arc, the effective power of which is equal to the sum of the effective powers of the laser and arc heat sources. For example, a maximum speed of laser-arc welding with full penetration of stainless steel plates 1 mm thick at Q = 285 W and I = 60 A is, according to the calculations, 90 m/h (in the experiments the maximum value of the speed of welding with full penetration, $v_{max} \approx 60$ m/h, was limited by the capabilities of a device used for displacement of a sample), which is almost 4 times as high as the maximum speed of argon-arc welding, v_{max} = = 23 m/h, achieved at I = 90 A. It should be noted that with the selected parameters of the laser and arc heat sources a relationship of q_a (I = 90 A) $\approx q_a$ (I = = 60 A) + q_l (Q = 285 W) is met.

Therefore, the suggested mathematical model of thermal processes occurring in laser-arc welding using the YAG laser and argon arc, despite its simplicity, enables the penetration profiles in the combined effect on a workpiece by the laser beam and electric arc to be calculated at a sufficient accuracy, allowing for their interaction on the metal surface. This makes it possible to use the calculated data obtained by using this model to select parameters of a specific laser-arc welding process.

In conclusion, the author would like to thank A.I. Bushma for the assistance in making the calculations.

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RECONDITIONING OF EXCHANGEABLE PARTS USING LASER TECHNOLOGIES

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ABSTRACT

The paper describes the features of laser-powder spraying and laser surfacing application for repair and restoration of the specified contour of ship machinery parts, in particular, piston rods. Advantages of application of laser restoration technologies are demonstrated.

Key words: *laser restoration technologies, coating application by spraying, surfacing, reconditioning*

Laser technologies are regarded to be promising and efficient technologies of the future in many manufacturing areas.

Unlike laser cutting and laser welding, that have already been widely accepted by industry, laser processing of the surfaces of various materials is used only by a few specialised enterprises. Training-Research Institute of Meklenburg-Vorpommern Land developed practically feasible and cost-effective variants of the process of laser spraying of coatings on ship machinery parts.

Repair by laser-powder spraying. In reconditioning by laser-powder spraying the filler material is applied onto the item for restoration of the specified contour (Figure 1). Similar and dissimilar filler materials are used, for instance, high-quality wear-resistant materials or superplastic alloys.

This technology envisages feeding the filler powder by blowing it into the molten pool on the item in the form of a jet of gas and powder mixture. The powder melts in the zone of the laser beam impact and quickly solidifies to form a coating in the shape of a bead. In this case the substrate surface melting is minimal, this being sufficient for metallurgical bonding of the coating with the base material, with an extremely low degree of mixing of 5 %.

In order to produce reliable coatings, it is necessary to take three conditions into account simultaneously, namely achievement of the required strength of the structure coating, suitability of the material for coating and ability to perform spraying on the shop floor. Each of the above conditions depends on the material, technology and structure, and, therefore, cannot be considered separately.

The ability to select material combinations, technology and structure in reconditioning and repair, unlike manufacturing new items, is limited by that the appropriate operating requirements and base material of the structure have already been specified.

Repair of ship machinery parts by laser surfacing. Let us consider reconditioning of piston rods in greater detail. Two piston rods were damaged in fabrication by a defective lathe tool — a circular groove of 1 mm width and 1.2 mm depth was formed. Depth of finish treatment of piston rods was 0.2 mm.

The base material of the parts, Sk45, was characterised by a high sensitivity to the thermal cycle of surfacing, manifested in higher hardness of the substrate. In connection with a great (1.5 t) weight of the parts, the cooling rate was extreme from the view point of self-hardening.

The coating materials and technology should be selected so, as to allow producing a joint, capable of reliably withstanding the high inner stresses, developing as a result of extreme conditions of hardening, as well as working loads.

The material, defect geometry and treatment condition required a local surfacing process with minimal heat input, that can only be implemented by applying laser-powder spraying.

Selection of the variant of laser-powder spraying process was conducted to meet the following requirements: recess filling; temperature mode, guaranteeing absence of cracks in the HAZ material and during coating deposition; tempering of the adjacent material zones (lower hardening in the HAZ metal); ability to apply the selected coating material. Coating material selection should be performed, taking the fol-

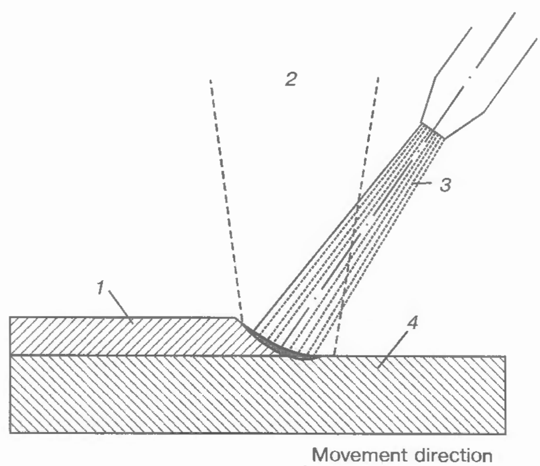

Figure 1. Block-diagram of powder spraying by a laser beam: *1* — coating; *2* — laser beam impact zone; *3* — gas-powder mixture; *4* — base metal

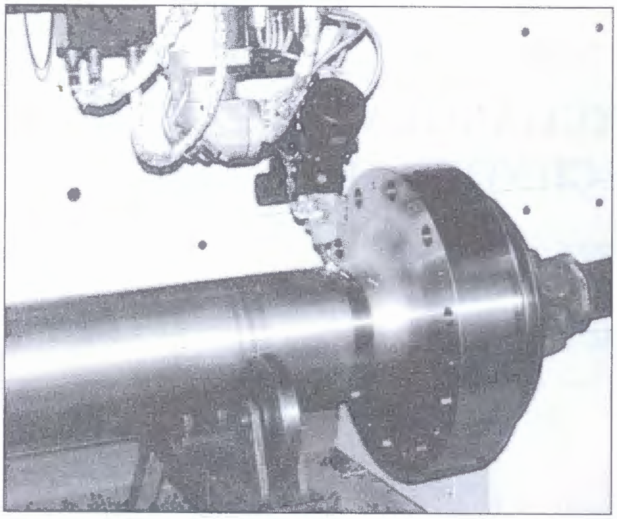

Figure 2. Laser-powder spraying of piston rod by CO_2-laser

lowing properties into account: tension, susceptibility to hardening, strength properties, material ductility for inner stress relieving.

Spraying was performed with a CO_2-laser, stellite 21 was selected as the coating material, cobalt being the base (Figure 2). Laser-powder spraying guaranteed identical work results on samples and actual parts.

Spraying was followed by local heat treatment with CO_2-laser for tempering of the HAZ metal, located near the item surface. The aim of tempering, using the laser beam, was to lower the hardness from $HV_{0.3}$ 700–780 to 420. During tempering the coating material proper was not remelted, so that its hardness was practically unchanged (Figure 3).

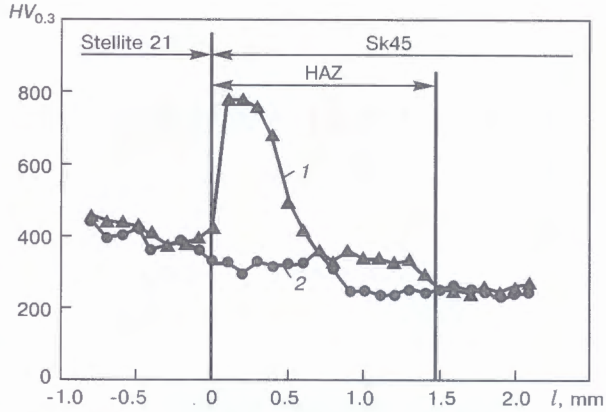

Figure 3. Hardness profile of a 15 kg sample of Sk45 after laser-powder spraying without tempering (1) and after tempering, using CO_2-laser (2) (l — measurement point spacing)

Grinding of the laser-powder coating of stellite 21 produced good results, and the required surface roughness tolerances of 0.05 μm were ensured.

Process duration (surfacing plus tempering) of piston rod repair was 90 min. Piston rods were approved by German Lloyd for a wide use in container shipping. Parts of the total cost of DM 30000 have been repaired and commissioned at less than DM 2000 cost.

The above case illustrates the rationality of applying laser surfacing in repair technologies, compared to the traditional technologies, for localising the thermal impact on the item being restored, as well as minimising the material removal in finish machining. In addition, laser-powder surfacing can be used for repair of parts of ship and agricultural machinery, making tools and steel and plastic items.

Application of laser processing initiated further change in reconditioning technologies.

IMROVEMENT OF THE EFFICIENCY AND QUALITY OF LASER PROCESSING OF MATERIALS

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ABSTRACT

The paper presents the results of calculation and experimental studies of the technologies of laser welding of magnet core plates and laser cutting of semiconductors. Capabilities of laser technologies are demonstrated in terms of improvement of process efficiency and processing quality.

Key words: *laser processing (welding and cutting), process efficiency, processing quality, power and radiation energy density, semiconductor materials, core*

Improvement of efficiency and quality of material processing is one of the ways to raise production and economic indices. This is usually achieved at minimal cost by improving the available equipment, tool designs, optimising the processing modes, supplying additional inexpensive kinds of energy to the cutting zone, etc. Among the methods, effectively used to improve the efficiency and quality of laser technology, is optimisation of power density distribution in the focal spot $W_P(x, y)$ (or integral characteristic — energy density $W_E(x, y)$) of the laser flow in its impact zone. This method is applicable for improvement of various technological processes (TP), namely strengthening, welding, surfacing, cutting, etc. Change of power density $W_P(x, y)$ is usually achieved through application of special focusing systems, that convert the distribution of laser flow, coming out of the laser cavity, and change of energy density $W_E(x, y)$ is produced by the focused beam scanning the surface being processed [1–10].

This paper gives the results of studying TP of laser processing of materials by scanning laser radiation, obtained by the authors during investigation and optimisation of the technologies of magnet core welding and semiconductor cutting.

Experimental procedures and equipment used. A number of TP, where a focused laser beam is used as the processing tool, such as annealing, strengthening, welding (without «key-hole» penetration) [11], can be described by a non-linear, non-stationary multidimensional equation of heat conductivity, taking into account phase transformations with the appropriate initial and boundary conditions:

$$c(T)\rho(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right); \qquad (1)$$

$$c_V(T) = c_V'(T) + Q_f\,\delta(T - T_f); \qquad (2)$$

$$\frac{\partial T}{\partial x}\Big|_{x=0,\ x=H_x} = 0;$$
$$-\lambda(T)\frac{\partial T}{\partial z}\Big|_{z=0} = [1 - R(T)]W_P(x, y, t); \qquad (3)$$
$$T_{\text{start}} = 250\ ^\circ\text{C},$$

where x, y, z, t are the spatial and time co-ordinates; $\rho(T)$, $c(T)$, $\lambda(T)$, $R(T)$ are the dependencies of density, heat capacity, heat conductivity and optical properties of the part material being processed on temperature T; c_V is the heat capacity of the material being processed at a constant volume; c_V' is the heat capacity, without allowing for the phase transformation; Q_f is the phase transformation enthalpy; T_f is the phase transformation temperature; δ is the delta function; H_x, H_z are the part length and thickness; $W_P(x, z, t)$ is the power density of the focused laser beam, depending on the spatial and time co-ordinates. Therefore, the process of laser welding of the magnet core was studied through computational experiments, using as the process model the above system of equations, solved by the method of finite differences. The data on temperature dependencies of thermo-physical properties of electrical steel with silicon volume fraction of 2.2 % corresponded to those given in [12], of optical properties — to those in [13], and they were interpolated by cubic splines. Focal spot diameter d_0 and flow intensity distribution $W_P(x, y)$ were determined by the method of «scanning» aperture with subsequent processing by the least squares method. Function $W_P(x, y)$ had the following form:

$$W_P(x, y, t) = \frac{4P(t)}{\pi d_0^2}\exp \times$$
$$\times \frac{(-4C_{\text{conc}}((x_c - x)^2 + (y_c - y)^2)}{d_0^2}, \qquad (4)$$

where x_c, y_c are the co-ordinates of the beam center. The coefficient of concentration $C_{\text{conc}} = 2$.

In the case of a focused laser beam scanning by an elliptical law and processed part displacement

Table 1. Operation sequence in investigation of the technological processes

No.	Magnet core welding [6, 9, 10]	Semiconductor cutting [7, 8]
1	Process model — equations (1)–(7)	Process model — equation (8)
2	Computational experiment	Preplanning, selection of process factors, model kind, experiment plan
3	Experimental check of the obtained results	Implementation of the experiment, process model construction, verification of the suggested hypothesis
4	Result analysis	Result analysis, process optimisation
5	Experimental check of optimal modes, making test batches of parts	

along axis OX, the co-ordinates of beam center $x_c(t)$ and $y_c(t)$ and energy density distribution of the focused beam are calculated by the following equations, respectively:

$$x_c(t) = x_0 + V_x\, t + A \cos(2\omega t);\quad y_c(t) = y_0 + B \sin(2\omega t); \tag{5}$$

$$W_E(x, y) = \int_0^{t_{move}} \frac{P(t) \exp\{-C_{conc}\,[(x(t)-x)^2 + (y(t)-y)^2]/r_0^2\}}{\pi r_0^2}\, dt, \tag{6}$$

where x_0, y_0 are the co-ordinates of the beam axis initial position; ω is the scanning frequency; A, B are the scanning amplitudes.

In order to determine the maximal pulse power P_{max}, modelling of the process in the pulsed mode of the laser operation was performed, using a relationship, allowing for the equality of the mean beam power P_m and beam energy in different generation modes:

$$\int_0^{\tau} P(t)\, dt = \frac{P_m}{\nu}, \tag{7}$$

where τ, ν are the duration and repetition rate of laser pulses.

When analysing the results of the computational experiments, the processing time and quality were determined by the time of existence and depth of the weld pool. Calculations were performed for various magnitudes of processing speed (v_x = 1, 5, 10, 15, 20 mm/s), scanning frequency (ω = 0, 55, 65, 75 Hz), two laser generation modes (continuous and pulsed) and constant scanning amplitudes (A, B = = 0.3 mm) and focal spot diameter (d_0 = 0.3 mm) [6, 9, 10].

In connection with the fact, that the modes of precise laser processing (hole drilling, cutting, etc.) still have not been adequately described by physical dependencies [5, 11], modelling and optimising of the process of semiconductor laser cutting was performed by experiment planning methods [7, 8, 14], i.e. the process model for each response y_l (cut width at the entrance S_{ent} and exit S_{exit}, respectively, cut side roughness R_z) were calculated, using equation

$$y_l = b_0 + \sum_{i=1}^{i=k} b_i\, x_i + \sum_{i\neq j=1}^{i\neq j=k} b_{ij}\, x_i\, x_j + \sum_{ii=1}^{ii=k} b_{ii}\, x_{ii}^2, \tag{8}$$

where k is the number of process factors x_i; b_0, b_i, b_{ij}, b_{ii} are the coefficients of the regression equation; i, j are the indices.

Welding and cutting TP were studied by the classical procedures, with their implementation sequences

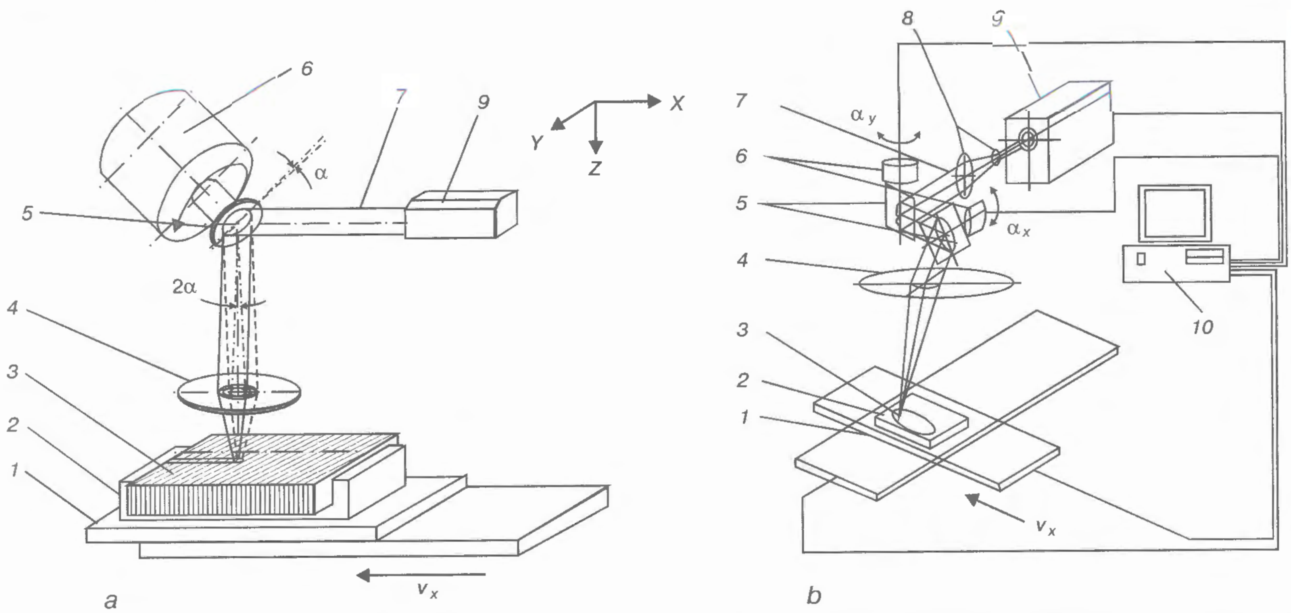

Figure 1. Schematics of experimental set up for studying the process of welding (a) and semiconductors cutting (b): *1* — worktable; *2* — fixture; *3* — sample; *4* — focusing lens; *5* — rotating mirror; *6* — drive; *7* — laser beam; *8* — telescopic system; *9* — source; *10* — PC

Table 2. Levels of process factors variation, when studying the process of semiconductor cutting

No.	*Level and interval of factor variation*	*Code*	v_x, *mm/s*	ν, *kHz*	*F, mm*	Δ*F, mm*	ω, *Hz*	α, ″
			X_1	X_2	X_3	X_4	X_5	X_6
1	Main level	0	15	23.4	45	–0.05	70	120
2	Variation interval	1	10	20.0	5	0.05	50	60
3	Upper level	+1	25	43.4	50	0	120	180
4	Lower level	–1	5	3.4	40	–0.10	20	60

given in Table 1, and diagrams of the used experimental set ups are shown in Figure 1.

When studying the process of laser welding, experimental check of the results, obtained when solving equations (1)–(7) was carried out in the experimental set up (Figure 1, *a*), incorporating YAG source of 180 W power, operating in the continuous and pulsed generation modes ($\nu_p = 150$ Hz, $t = 4.5$ ms); scanning system (rotating mirror, fastened on an electric motor shaft) and worktable, moving at the speed of 1–20 mm/s. Micromotor armature core stack was clamped in a special fixture and processed in different modes, calculated earlier by solving equations (1)–(7). In view of the ability to compare the results of the computational and full-scale experiments, investigations were conducted, using a passive strategy (with successive change of processing speed, scanning frequency and laser generation modes), with three experimental results derived for each experimental point. Weld samples were further subjected to tensile testing, and used to prepare macrosections, on which the depth and width of the melt pool was determined [6, 9, 10]. Weld pool parameters and cut width were measured in BMI-1Ts and PMT microscopes, and cut surface roughness — in binocular Linnik microscope (MIS-11).

The process of laser cutting of semiconductors [7, 8] was studied in an experimental set up (Figure 1, *b*), consisting of YAG laser with *Q*-factor modulation (pulse repetition rate $\nu = 3.4$–54 kHz, average radiation power $P_m = 20$ W) and two-coordinate scanning system (driven by reversible piezoceramic step motors). Blanks of polycrystalline silicon 0.3–0.5 mm thick were mounted on the worktable, having the displacement speed of up to 30 mm/s, and were processed in keeping with the plan of experiment (Rechtschafner saturated plan [14] for six process factors), experiments being conducted three times for each experimental point. Table 2 gives variation ranges of the following process factors: part displacement speed v_x (X_1); pulse repetition rate ν (X_2); focal distance of focal lens *F* (X_3); value of defocusing of focusing optics Δ*F* (X_4); frequency ω (X_5) and scanning amplitude α (X_6).

At laser beam scanning by the schematics, given in Figure 1, amplitude *A* and *B* of the focused beam displacement over the part surface, according to equation (5), depends on the angle of rotation of scanning mirror α and lens focal distance *F*. Unlike the process of laser welding of the magnet core, when scanning amplitude $A = B = 0.3$ mm (values *F*, d_0 and α are constant) in investigation of the process of semiconductor laser cutting the amplitude of scanning over the part surface changed in the coset space in the range of 20 to 60 μm.

Analysis of the results of preplanning and computational experiments. The influence of additional focused laser beam scanning on the result of material processing is the most vividly demonstrated, when comparing the shape of energy density distribution of focused laser radiation over the part surface with the appearance of the laser scribe (cut). Figure 2 shows the distribution of energy density in spatial co-ordinates, derived when solving the system of equations (4)–(6) in the PC, as well as the result of processing — appearance and shape of the laser scribe. These data are given for the case, when laser radiation ($P_m = 20$ W, $\nu = 3.4$ kHz) was focused into a spot of diameter $d_0 = 0.04$ mm and was scanned by a circular (Figure 2, *a, b*) and linear law (Figure 2, *c*) at different speeds of the part displacement [7, 8]. As is seen from the above relationships, the shape of laser scribe completely corresponds to the law of variation of function $W_E(x, y)$ in the spatial co-ordinates. At the moments of the focused laser beam and the part moving towards each other, when their summary speed v_Σ is equal or close to zero, an abrupt increase of value $W_E(x, y)$ and of the scribe depth, respectively (up to complete perforation of the blank) is found.

Further scanning by the focused laser beam also influences the processing result in laser welding. Change of energy density $W_E(x, y)$, as shown by numerical solution of equations (1)–(7) [6, 9, 10], leads to the change of thermal cycles, heating depth, time of liquid phase existence, etc. Figure 3 shows the graphs of the change of temperature $T(z, t)$, depending on time, at different depth *z* of the surface being processed, as well as of focused radiation power density W_P in laser beam processing in the continuous mode of laser generation ($P_m = 180$ W, $d_0 = 0.3$ mm). Figure 4 shows similar dependencies, obtained for the pulsed mode of laser generation ($P_m = 180$ W, $d_0 = 0.3$ mm, $\nu = 150$ Hz, $t = 4.5$ ms). In both the cases the part displacement speed was equal to 0.3 m/min.

Having analysed the results of calculations, the fragments of which are given in Figures 3, 4, the following should be noted:

• thermal cycles reproduce the periodicity of the heat source appearance (focused laser beam), this dependence decreasing with greater distance to the sur-

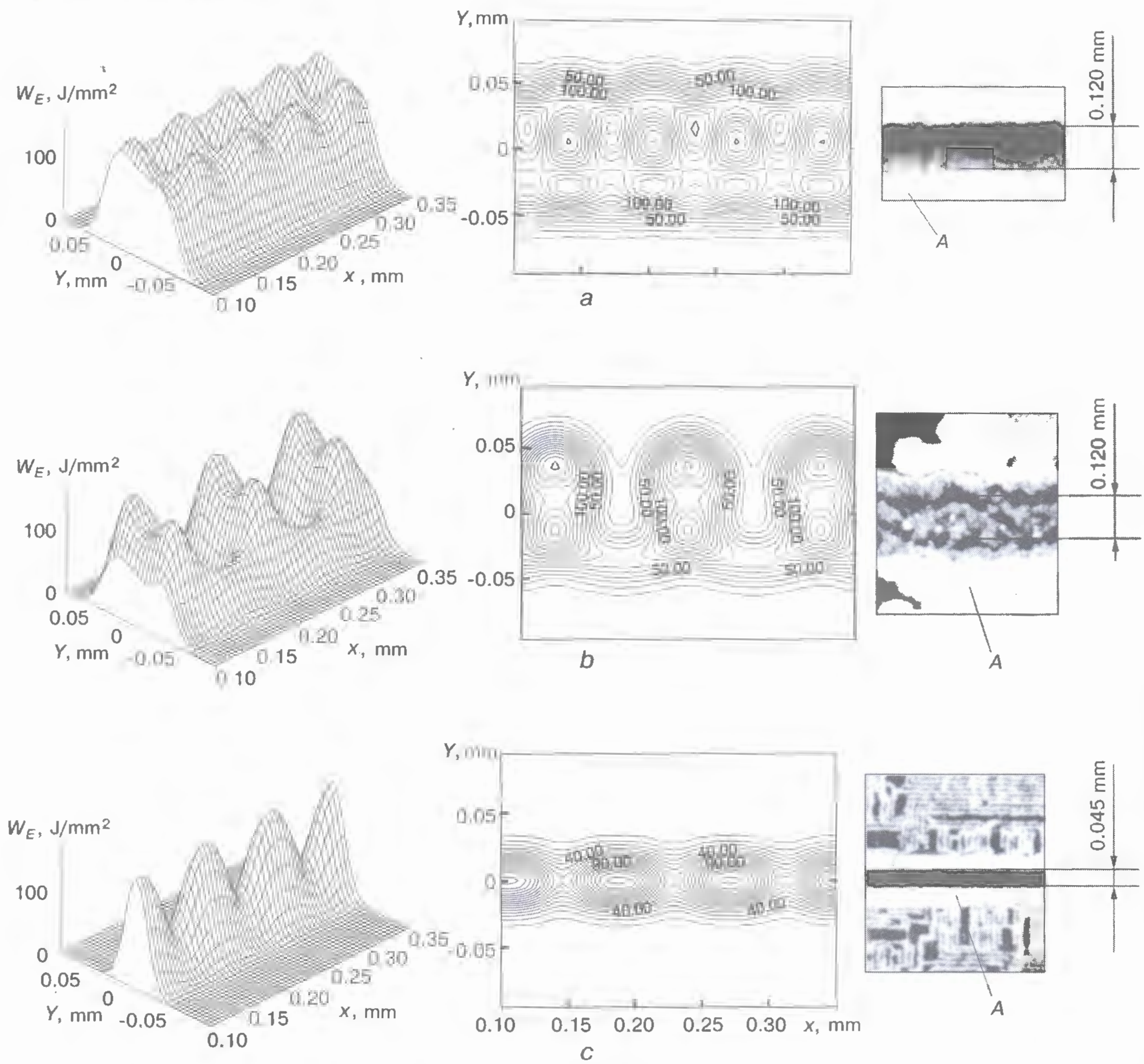

Figure 2. Energy density distribution $W_E(x, y)$ of focused laser radiation in spatial co-ordinates (*left*) and in one of the sections (*middle*), and appearance of the appropriate laser scribe after beam processing at the speed $v_x = 5$ (*a*) and 8 (*b*, *c*) mm/s, $\nu = 3.4$ kHz (*right*): *a*, *b* — circular scanning ($A = B = 0.04$ mm); *c* — linear scanning; material is single-crystal silicon; *A* — laser erosion products

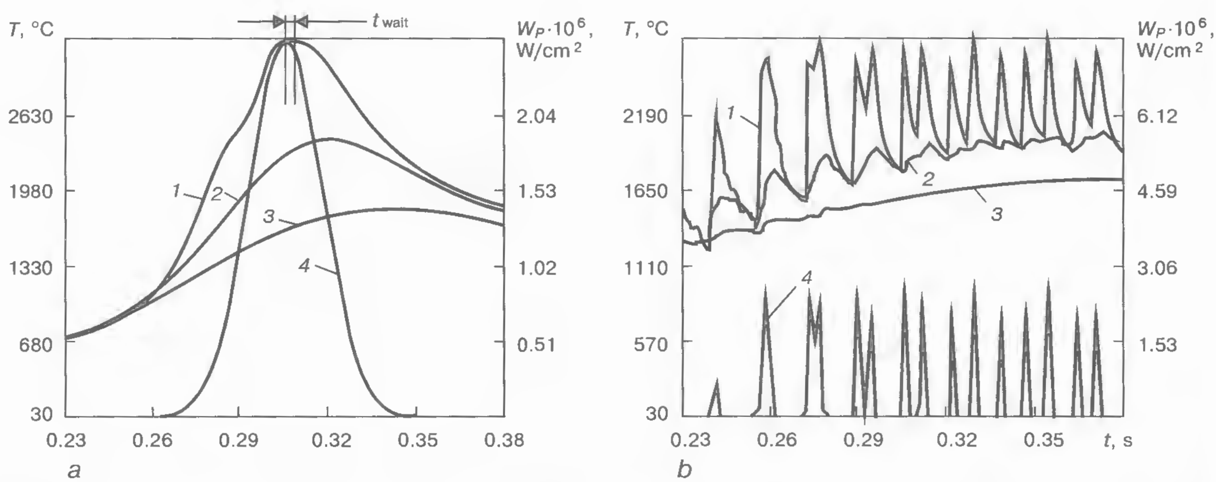

Figure 3. Dependencies on time t for temperature $T(z)$ at different depths from the irradiated surface (*1* $z = 0$; *2* $z = 0.09$; *3* $z = 0.25$ mm) and laser radiation power density W_P (*4*) in welding by a focused laser beam at different scanning frequency: *a*   0; *b*   55 Hz ($A = B = 0.3$ mm); material is electrical steel

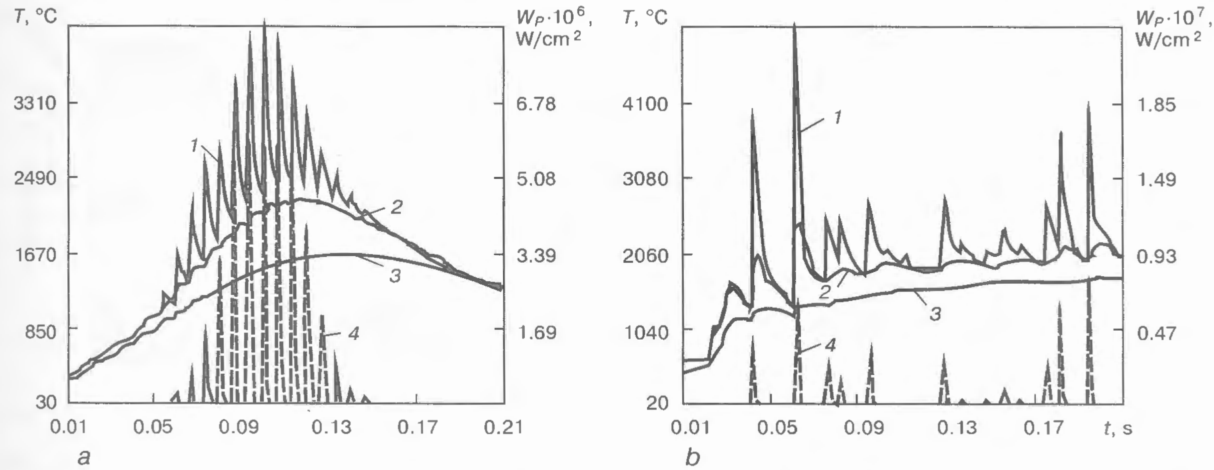

Figure 4. Dependencies on time t for temperature $T(z)$ at different depths from the irradiated surface (*1* — $z = 0$; *2* — $z = 0.09$; *3* — $z = 0.25$ mm) and focused laser radiation power density W_P (*4*) in welding with the scanning frequency of 0 (*a*) and 55 (*b*) Hz ($A = B = 0.3$ mm); material is electrical steel

face being processed, because of the inertia of the heating system and damping influence of phase transformations in the material being processed (Figures 3, 4, curve *3*);

• time lag t_{wait} before reaching the maximal temperature (both on the sample surface and in its depth), relative to the moment of maximal laser radiation energy input, is recorded;

• in all the studied coset space (Figures 3 and 4 give the results of solutions for some particular cases) the surface temperature is higher, than the steel rimming temperature [6, 9, 10]. Metal vapours and erosion plasma reduce (through absorption and reflection) the amount of laser energy, reaching the surface being processed, especially in the case of low processing speeds. Increase of lag t_{wait}, related to increase of the total speed of the part and the focused beam, results in the beam intensity peak «moving away» from the plasma, thus increasing the effectiveness of interaction of the focused laser beam with the surface being processed;

• in the pulsed generation mode (with the same average radiation power) the power of individual pulse is more than 3 times higher, than the average one, and is equal to 600 W, therefore, processing in this mode allows achieving a greater weld pool depth and time of its existence, compared to the continuous generation mode.

In processing by a scanning laser beam, the average surface temperature decreases, because of redistribution of energy density $W_E(x, y)$ (see Figures 3, *b* and 4, *b*). However, the time of the weld pool existence becomes longer, due to multiple passage of a focused beam over the processing zone and longer input of energy that is more effectively absorbed by the part surface (because of continuously moving away from the plasma) and promotes a balance on the liquid–solid interface. As in case of laser processing of semiconductors (see Figure 2), an abrupt increase of surface temperature is observed, when the summary speed of the focused radiation beam and the part being processed is equal (or close) to zero (see Figure 3, *b* and 4, *b*). Surface temperature surges are especially noticeable in the pulsed processing mode at the moments of time, when $v_\Sigma \cong 0$ that coincides with the moment of generation (Figure 4, *b*).

Figure 5 presents the resulting dependencies of weld pool maximal depth $h_{m\,max}$ and existence time t_m on part displacement speed v_x in processing electric steel by the laser beam, focused into a spot with $d_0 = 0.3$ mm, in the pulsed generation mode ($P_m = 180$ W, $\nu = 150$ Hz, $t = 4.5$ ms), for different scanning frequencies. As is seen from these dependencies, processing at low irradiation speeds produces welds with weld pool maximal depth and time of existence. However, because of processing zone overheating, it is rational to perform processing at maximal irradiation speeds with focused beam scanning. With the increase of scanning frequency up to 75 Hz, a balance is observed between the applied laser radiation energy and the heat, removed from the laser impact zone, due to natural heat conductivity. In this case the melt pool depth is smaller, than in irradiation with the frequency of 65 Hz. However, because of the high displacement speed, the scanning beam continuously

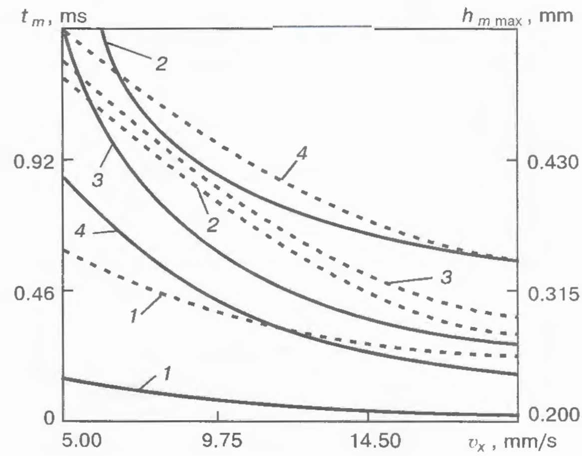

Figure 5. Dependence of maximal depth of the molten pool $h_{m\,max}(t)$ (solid curves) and time of its existence (dashed curves) on the speed of part displacement v_x in processing electrical steel by a laser beam with scanning frequency $\omega = 0$ (*1*), 55 (*2*), 65 (*3*) and 75 (*4*) Hz in the pulsed generation mode

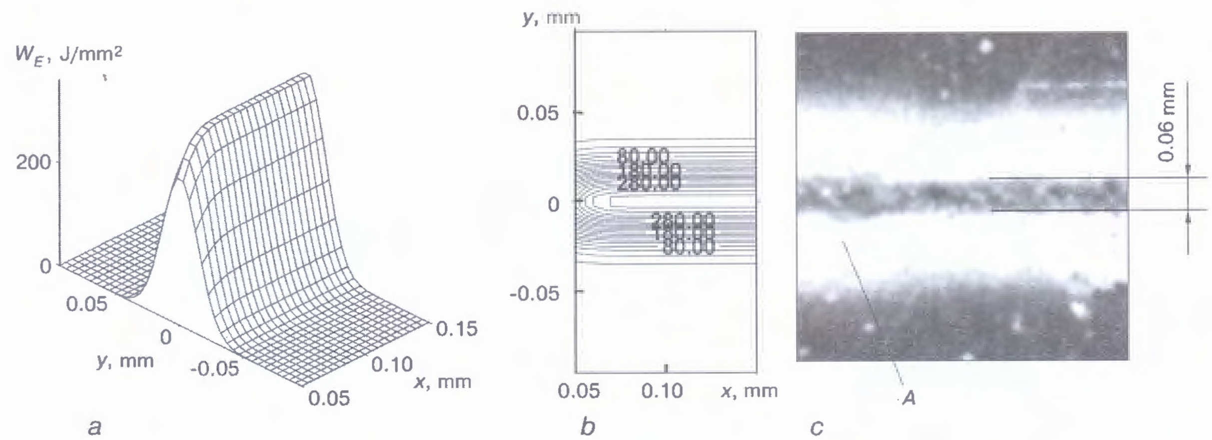

Figure 6. Distribution of energy density $W_E(x, y)$ of focused laser radiation in spatial co-ordinates (*a*) and in one of the sections (*b*); *c* — appearance of respective laser scribe after processing by this radiation (d_0 = 0.04 mm, P_m = 20 W, v = 3.4 kHz, v_x = 5 mm/s); material is single-crystal silicon 0.3 mm thick; *A* — products of laser erosion

preheats the melt, extending its life, this, certainly, affecting the welding quality.

Similar to laser welding, in laser cutting of semiconductors, low-speed processing leads to a larger HAZ, greater amount of the melt in the cut zone and subsequent re-filling of the formed scribe with the melt (Figure 6).

Analysis of the results of the conducted experiments and process optimisation. Modelling of the developed TP was conducted in keeping with the earlier described general research strategy. In laser cutting of semiconductors, focused beam scanning was performed in the plane, coinciding with the direction of the part displacement speed vector, as this is exactly the mode, providing the minimal cut width (see Figure 2, *c*). After implementation of the experiment

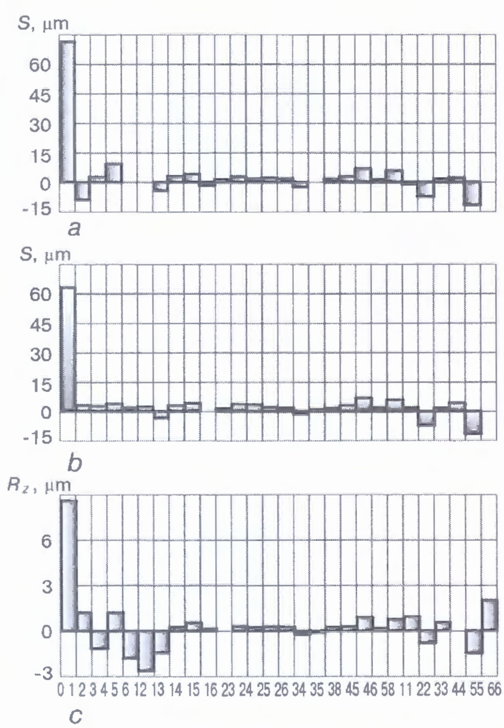

Figure 7. Rank diagrams of the coefficients *b* in the regression equation, describing TP of laser processing of polycrystalline silicon 0.3–0.5 mm thick; abscissa axis indicates respective indices of the coefficients

plan, calculation of the coefficients of the regression equation (for each response) and checking the statistical hypotheses (they were confirmed), adequate models of TP of laser cutting of semiconductors were obtained [7, 8], given in Figure 7 in the form of rank diagrams. As a result of analysis of these dependencies it should be noted, that in the studied coset space (Table 2 gives the boundaries of change of independent variables), those process factors have the greatest influence on the processing result, that influence the energy density redistribution along the cut line, namely scanning frequency and amplitude. This statement is especially valid for the model, describing the dependence of the cut sides roughness (Figure 7, *c*), as R_z parameter is the most critical to the frequency of occurrence of such moments, when the total speed of the part displacement is equal or close to zero (see Figure 2, *c*). The linear and quadratic sets of coefficients have the strongest influence on R_z dependence on the process factors, namely scanning frequency from the linear set, scanning frequency and amplitude from the quadratic set (coefficients b_5, b_{55}, b_{66}).

It should be noted, that in the entire studied coset space, a through-thickness cut is formed due to a layer-by-layer cutting of the processed material (because of multiple passage of the focused beam). In addition, as a result of $W_E(x, y)$ redistribution, it is also due to perforation of elementary holes, formed at moments of time, corresponding to $v_\Sigma \cong 0$, and crossing each other.

Scanning frequency of laser radiation also has the maximal impact on welding result. Graphic interpretation of the results of experiments on studying the TP of magnet core laser welding, is given in Figure 8. The presented dependencies demonstrate, that the maximal dimensions of the weld pool, namely depth (Figure 8, *a*), width (Figure 8, *b*) and maximal rupture strength (Figure 8, *c*) are found, when a scanning focused laser beam is used as the tool. Analysis of the results, obtained from the performed calculations (see Figures 3 and 5) and experiments (Figure 8) demonstrates their qualitative coincidence. As shown by the

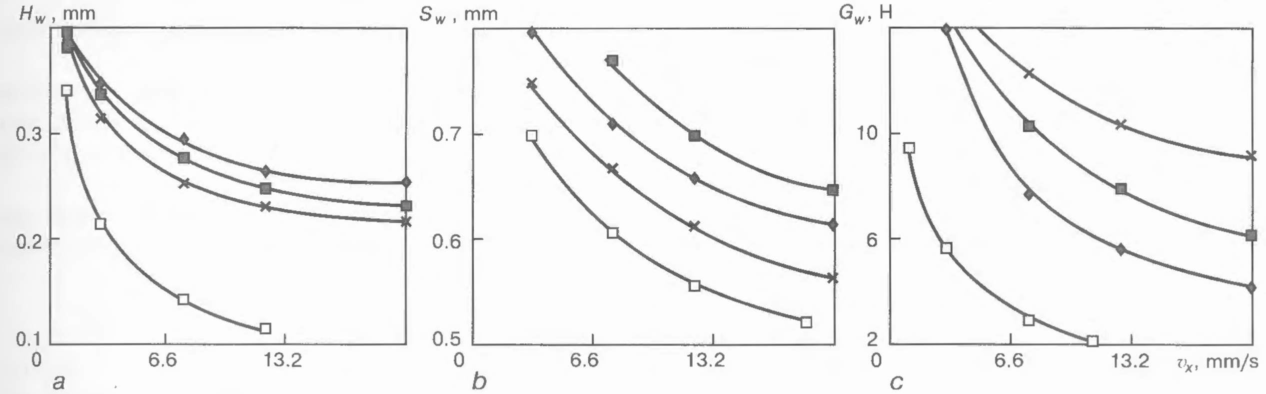

Figure 8. Dependence of depth H_w (*a*), width S_w (*b*) and rupture strength G_w (*c*) of a weld on part displacement speed v_x in electric steel processing by a laser beam (P_m = 180 W, d_0 = 0.3 mm, t = 4.5 ms, ν = 150 Hz) with different scanning frequency: ❐ — 0; ◆ — 55; ◆ — 65; × — 75 Hz

performed studies, maximal rupture strengths are observed in processing by a focused laser beam, scanning with the frequency of ω = 75 Hz (Figure 8), this being related, as was mentioned, not to the maximal depth of the melt pool, but to the time of its existence (see Figure 5, curve *4*).

It should be noted, that in the case of a continuous generation mode at processing speeds higher, than 13 mm/s, it was not possible to produce a sound permanent joint of magnet core plates in the entire studied range of beam scanning frequencies. This is, probably, related to the short time of existence of the liquid pool — less than 0.12 s (see Figure 5) and incomplete diffusion process, respectively.

Thus, in the studied range of variation of the part displacement speed, scanning frequency and laser generation modes, it is rational to perform welding of the micromotor rotor plates at the limit speed (to achieve the maximal operation efficiency) with scanning amplitude within the focal spot and frequency, equal to 75 Hz. It is also rational to use similar modes to weld transformer plates. Despite the fact, that one weld prevents the plates falling apart, their spreading (not tight enough contact between the plates on the side, opposite to the processed one) is found, because of low-quality stamping, especially with the die wear. Therefore, the recommendation is to apply the welds parallel to the direction of their mechanical fastening.

The established modes were used to process a test batch of micromotors and transformers, whose rig testing demonstrated their correspondence to the items, made by the standard technology.

When the results, derived using equations (1)–(7) (implicit link between the processing result and process factors) in investigation of materials laser processing TP, do not satisfy the technologist, optimisation of these processes is also possible, but its requires considerable consumption of computing power [15].

Unlike process models, incorporating an implicit link between the processing result and process parameters, the models, obtained by the experiment planning methods, are ideally suited to handle optimisation problems, solved by the non-linear programming methods [15, 16]. These methods allow for the limited nature of the coset space, multi-criterial nature of the process, etc. [16]. Thus, optimisation of the TP of laser cutting of semiconductors included establishing the processing modes, providing minimal roughness of the cut sides and maximal efficiency in a limited design space:

$$R_z(x_i) = 0; \qquad (9)$$

$$-1 \le x_i \le +1,\ x_1 = +1. \qquad (10)$$

It was assumed, that the cut width should not exceed 50 μm:

$$30 \le S_{ent}(x_i) \le 50. \qquad (11)$$

Optimisation problem was solved by the method of «penalty functions», re-arranging the system of equations (8)–(11) as follows:

$$F(x_i) = q_1\, R_z\,(x_i) + q_2\,[S_{ent}\,(x_i) - 50]^2 +$$

$$+\, q_2\,[S_{exit}\,(x_i) - 30]^2 + q_3 \sum_{i=1}^{k} |x_i|, \qquad (12)$$

where q_1, ..., q_3 are the weight coefficients. Hooke–Jives method was used as the method-organiser of the search [16].

After solving problem (8)–(12) and experimental check of the results, processing modes were established, that provide laser cutting of polycrystalline silicon 0.3–0.5 mm thick with 8 μm roughness of the sides of the cut 0.045 mm wide. Processing speed was 25 mm/s, modulation frequency was 44 kHz, lens focal distance being 40 mm with defocusing of −0.1 mm, scanning frequency and amplitude of 80 Hz and 120″, respectively. It is obvious, that cutting of single-crystal silicon is also possible in the above modes. Further experiments demonstrated, that in this case (material was single-crystal silicon 0.3 mm thick) the cut width was 0.04 mm, while the side roughness was not less than 0.8 μm (measurements were limited by the measurement limit of Linnik microscope). Lower side roughness and smaller cut width are attributable to a stable thickness of the blank (unlike the polycrystal, where the thickness varies considerably). It should be noted, that use of kinematic equations (5) allows determination of such a law of relative displacement of the focused laser beam and the part, that minimises not only the cut width, but also the period of time of reaching $v_\Sigma \cong 0$. However, because of the complexity of the processes, proceeding in the processed material during evaporation, minimising of the distances between the points with zero summary speed in the focal spot and the part and of the roughness peaks, respectively, does not allow obtaining the optimal result.

The established processing modes were used to make a test batch of blanks (40 pcs), of which solar elements were later manufactured by the standard technology. Full-scale testing demonstrated, that their efficiency is by 5–6 % higher, than that of the solar elements, manufactured by the conventional laser cutting, i.e. without scanning (see Figure 6). This is related to the fact, that the HAZ in standard samples is by 30 % larger (determined by I.A. Podchernyaeva's method of paramagnetic resonance), than that of samples, made by the developed technology.

CONCLUSIONS

1. Focused laser beam scanning within the focal spot allows improving the laser technology process efficiency and quality.

2. Improvement of processing efficiency and quality is attributable to redistribution of laser radiation energy density over the processed part surface and its more effective absorption by this surface.

3. In laser welding laser radiation scanning within the focal spot leads to lowering of the processed surface temperature and longer time of the weld pool existence.

4. In laser cutting of semiconductor materials higher efficiency and quality of processing is attributable to their layer-by-layer cutting and perforation (at moments of time, when the summary speed of the processed part and focused beam is close or equal to zero).

5. In laser cutting of semiconductors, the minimal width of the cut is guaranteed in the case, when the focused beam scanning is performed in a plane, coinciding with the direction of the part displacement speed vector.

6. In the studied coset space the highest welding efficiency can be achieved in the case of application of sources, operating in the pulsed generation mode with additional beam scanning.

7. Laser welding of magnet core plates does not impair the finished item parameters (compared to the standard technology).

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ASSURANCE OF QUALITY OF LAYERS MADE BY LASER SURFACING OR STRENGTHENING TREATMENT

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ABSTRACT

Method of changing the quality characteristics of surface layers produced by a laser surfacing or strengthening treatment is suggested. The feasibility of control of the cooling processes of the deposited layers by changing the space distribution of radiation power in the focusing plane is shown. Unique technical solutions were used for control of the space distribution of the laser radiation power.

Key words: *laser beam, laser surfacing, space distribution of power, focusing systems, cooling rate, heat source, residual stresses. cracks in surfacing*

The technology of surfacing with a use of energy of laser radiation is an effective method of restoration of dimensions of worn-out parts and imparting high physical-mechanical and service properties to their surface layers. Over the recent years, the processes of laser surfacing and treatment are studied very comprehensively in the industrialized countries, as they are a basis of the intensively developing waste-free technology of manufacture of parts, the so-called Rapid Prototyping method [1].

At present, a number of works has been made in which different methods of the laser surfacing [1, 2], mathematical models of accompanying heat and hydrodynamic processes [3, 4] are considered. It is shown that the laser surfacing is not, in principle, inferior, and in some cases even superior to some methods of surfacing by the quality of the deposited layer, strength of welding of the parent and deposited metals, depth of penetration, level of deformations and other characteristics [5, 6].

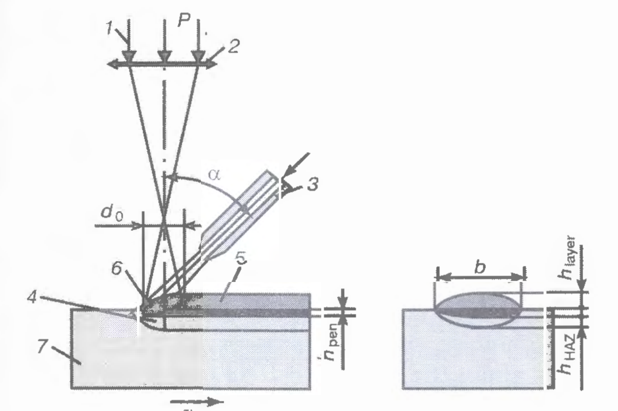

Figure 1. Scheme of the laser powder surfacing process: *1* — laser beam; *2* — focusing lens; *3* — gas-powder mixture; *4* — HAZ; *5* — deposited layer; *6* — weld pool; *7* — sample (h_{pen} — depth of penetration)

However, the application of different methods of the laser surfacing (including a powdered surfacing among them) is limited by several factors and, first of all, by the lack of effective methods of selection of conditions and filler materials that could provide, in general, the high reliability of the process and absence of defects (cracks, pores, non-fusions, etc.) in the deposited layer.

The laser powdered surfacing is performed as follows (Figure 1). The filler powder is fed by gravity or with the help of a transporting gas at angle α to the weld pool which is formed at the surface of the part being surfaced under the action of the laser radiation of power P, focused by a lens or a mirror, up to d_0 diameter of the focusing spot. During surfacing the part is displaced with respect to the laser beam at a rate v.

To have a more detailed description of the process, it can be presented in the form of a technological scheme (Figure 2) which is based on combination of several physical processes (radiation absorption, heating, melting, hydrodynamic processes in weld pool, solidification, diffusion, solid-state structural-phase transformations). The processes of melting and solidification are main among them and characterized by

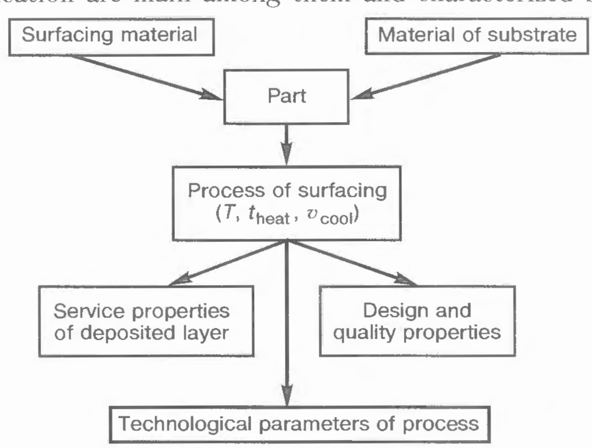

Figure 2. Laser gas-powder surfacing as a technological system

three main characteristics: temperature, rate (time) of heating and cooling.

The analysis shows that the main parameters of the process of the laser surfacing, which can influence the quality and geometry of the deposited layers are as follows: power of laser radiation and its distribution in the focusing spot, size of a focusing spot, consumption and direction of the powder feeding and speed of surfacing. By changing the parameters of the surfacing conditions it is possible to change the geometry of the deposited layer, to control its physical-mechanical and service characteristics. As a rule, the surfacing materials refer to hard-to-weld materials, and a main defect in the deposited layer is cracks, while nature and amount depend also on the laser surfacing condition parameters. The aim of the present work was to study a feasibility of prevention of crack formation by using control of heat processes in the depositing and parent metal during laser surfacing.

The feasibility of changing the nature of solidification of the weld pool and rate of cooling in the zone of surfacing by changing the distribution of power of the laser radiation on the surface being deposited was studied. Different distributions of the radiation power were compared: Gauss, uniform, non-uniform with a steep and sloping front in the direction of the laser beam movement.

The numerical modelling of two-dimensional field in a metallic sample (in the form of a prism) with a coating at heat source movement along its surface was studied. The heat problem was considered in a non-linear statement. The non-linearity of the problem was determined by a dependence of thermophysical properties on temperature and coordinates, presence of phase transformations. Here, the thermophysical properties were preset in the form of hyperbolic equations. Relations of distribution of power density in the focusing spot W_P were interpolated similarly. During calculations of coefficients of polynomials the equality of an integral density of power in the focusing spot at different distributions of the radiation intensity was taken into account.

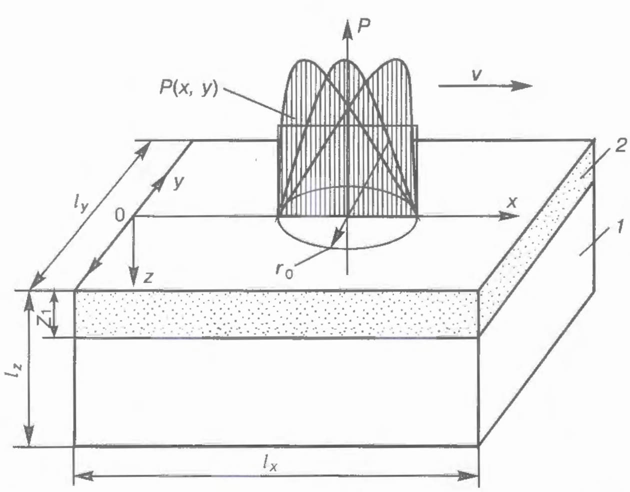

Figure 3. Scheme of plate heating in laser surfacing with different distribution of radiation power at the focusing surface: *1* — parent metal; *2* — deposited layer

The distribution of temperature $T(x, y, z, t)$ in the sample, along the surface of which the heat source is moved at a rate v along the axis $0X$, is described by the non-linear equation of heat conductivity using the following boundary and initial conditions:

$$c(T)\rho(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(K(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(K(T)\frac{\partial T}{\partial x}\right);$$

$$c_V(T)=c'_V(T)+\delta Q(T-T_f);\quad T_{\rm in}=T_0;$$

$$\frac{\partial T}{\partial x}\Big|_{x=0;\,x=l_x}=0;\quad -R(T)\frac{\partial T}{\partial z}\Big|_{z=0;\,z=l_z}=A(T)W_P(x,\,t);$$

$$\frac{\partial T}{\partial z}\Big|_{z=l_z}=0;$$

$$c=c_1(T,\,x,\,z)\big|_{x=x_1;\,z=z_1}+c_2(T,\,x,\,z)\big|_{x=x_2;\,z=z_2};$$

$$\rho=\rho_1(T,\,x,\,z)\big|_{x=x_1;\,z=z_1}+\rho_2(T,\,x,\,z)\big|_{x=x_2;\,z=z_2};$$

$$K=K_1(T,\,x,\,z)\big|_{x=x_1;\,z=z_1}+K_2(T,\,x,\,z)\big|_{x=x_2;\,z=z_2},$$

where $c_1(T)$, $\rho_1(T)$, $K_1(T)$, $c_2(T)$, $\rho_2(T)$ and $K_2(T)$ are the dependencies on temperature T of heat capacity, density and heat conductivity of deposited and parent metals, respectively; $W_P(x, t)$ is the distribution of power density of laser radiation in a focusing spot; x, z, t are the space and time coordinates; $c_V(T)$ is the volume heat capacity; $c_V(T) = c(T)\rho(T)$; $c'_V(T)$ is the heat capacity without allowance for the phase transition; δ is the Dirac's function; Q is the latent heat of the phase transition; $T_{\rm in}$ is the initial temperature of the part being surfaced; l_x, l_y, l_z are the sample dimensions; $A(T)$ is the dependence of absorptivity of surface on temperature T; x_1, z_1, x_2, z_2 are the sizes of material layers.

The scheme of the plate heating during surfacing, accepted for calculations, at different distribution of the radiation power along the focusing surface is given in Figure 3. The calculation of the temperature distribution and cooling rate in the surface layer at continuous action of the laser radiation was made using the following initial data:

Power of laser radiation P, W	1500
Diameter of focusing spot d_0, mm	2.5
Speed of beam movement v, m/min	0.2–0.5
Thickness of coating z_1, mm	0.5
Material of coating	PG-SR4
Material of substrate	steel 45
Dimensions of part $l_x \times l_y \times l_z$, mm	500 × 20 × 6

The above system of equations was solved using the method of finite differences with non-uniform pitches along the space and time coordinates.

Figure 4, *a* presents calculated dependencies of heating temperature on time at different depth from the surface of steel 45 (C — 0.45 wt.%; Fe — balance) sample, being surfaced with PG-SR4 (Cr — 15.0; Ni — 80.0; Si — 4.0; W — 4.0 wt.%) powder at Gauss (*I*), non-uniform sloping (*II*) and steep (*III*)

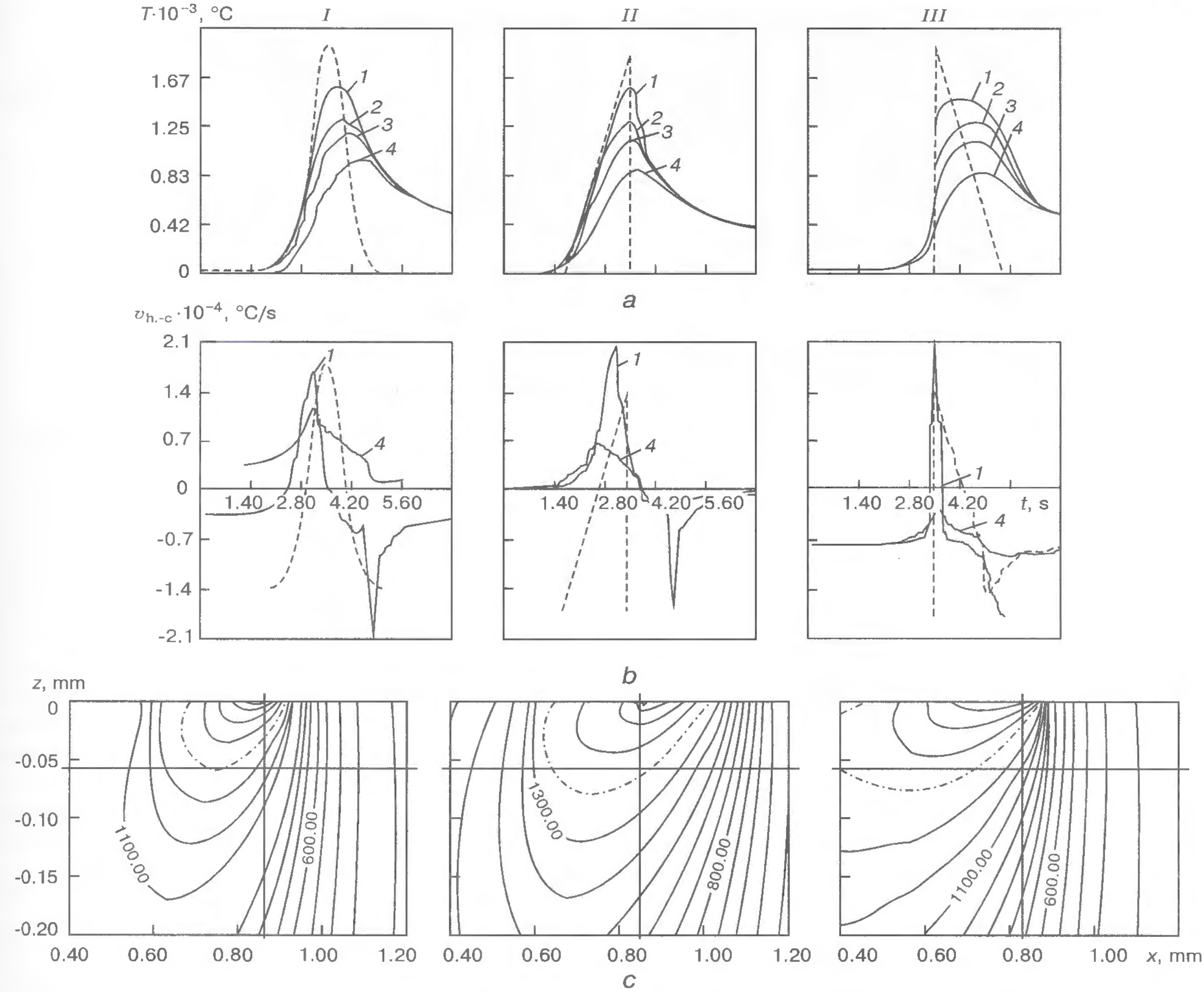

Figure 4. Dependencies on time for temperature of heating of sample of steel 45, deposited with powder PG-SR4 (*a*), rate of heating-cooling (*b*) at different distribution of power density in the heating spot (shape of distribution is shown by a dash line) at the distance of the deposited layer surface (0 (*1*); 2.5 (*2*); 4.5 (*3*); 8.5 (*4*) mm) and corresponding temperature fields of the deposited layer in coordinates *z*, *x* (*c*)

front of radiation power distribution in the direction of the heat source movement. Figure 4, *b* illustrates the dependencies of heating and cooling rates on time at different depth from the sample surface, while Figure 4, *c* shows the temperature fields in surface layer in coordinates *z*, *x* for corresponding distributions of the radiation power.

The non-uniform distribution of the radiation power in the focusing spot, when its maximum is shifted in the direction of the beam movement to the focusing spot edge, as compared with the traditionally used distributions (uniform, multimode, Gauss), provides the increase (by 40–80 %) in time of existence of the liquid phase (for conditions of calculation from 0.5 to 0.9 s); formation of weld pool, being non-uniform in depth and elongated in the direction of the heat source movement; decrease (by 2–3 times) in rate of cooling (for example, from $2.6\cdot10^4$ to $0.7\cdot10^4$ °C/s). The effect of influence of the non-uniform distribution of power is intensified with increase in the surfacing speed. This heat state creates additional conditions for the relaxation of thermal stresses in the deposited layer due to plastic deformation of plastic layers, which are located beneath.

In the course of the experimental investigations two distributions of the radiation power were compared: multimode, cylindrical with an axial symmetry (non-profiled beam), which is typical of many powerful CO_2-lasers, used for the surface strengthening and surfacing (Figure 5, *a*), and also non-uniform with a shifted maximum along the direction of beam movement to the focusing spot edge (profiled beam) (Figure 5, *b*).

The experiments were performed using the technological complex on the base of two powerful CO_2-lasers. To preset the necessary distribution of the power in the focusing spot and widening the range of the radiation power control, the appropriate focusing systems are used. A focusing system with a spherical mirror (Figure 6) was used for these purposes in our experiments [7]. This system consists of a radiator *1*, telescopic system *3* and spherical mirror *5* designed for changing the transverse section of the laser beam *2* which is fed to a focusing mirror *6* using flat rotatable mirrors *4*. The system can produce different distribution of power in the treatment plane *7* by changing the angle of beam incidence on the spherical mirror

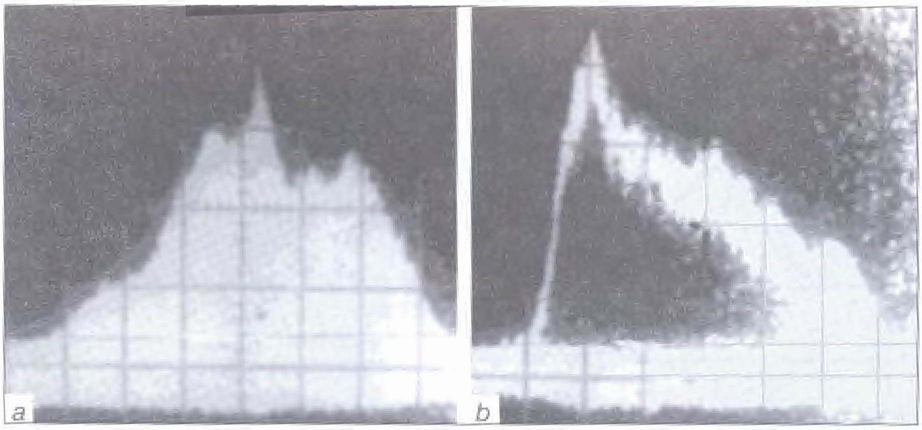

Figure 5. Oscillograms of space distribution of laser radiation power at the surface deposited: *a* — multimode, cylindrical with axial symmetry (non-profiled beam); *b* — non-uniform with a shifted maximum along the direction of laser beam movement to the focusing spot edge (profiled beam)

that is attained by matched vertical (along axis *z*) and angular (for angle *j*) displacements of the mirrors. To evaluate the radiation power distribution in the focusing plane, a procedure of scanning the transverse beam section by a diaphragm was developed.

A focusing system (Figure 7) presents a special interest. In this system a laser beam *1* with a circular distribution of the radiation power is introduced into a laser beam *2* with a uniform distribution of the radiation power. A telescopic system *3* is used for additional adjustment of the size of this introduced beam. With a change of the mutual position of axes of the beams by a rotatable mirror *4* and their focusing with lens *5*, it is possible to control effectively the radiation power *6* distribution in the treatment plane *7*.

In experiments the powders of different materials were deposited on the samples from steel 45 and heat-resistant alloy ZhS6K (Co — 10.0; Mo — 5.0; W — 5.0; Ti — 2.5; Al — 5.5 wt.%; Ni — base): self-fluxing alloy PG-SR4, mixture PS-12NVK (Cr — 15.0; Ni — 80.0; Si — 4.0; W — 4.0 wt.% + WC), master alloy KhTN (C — ≤ 0.12; Cr — 17.0–18.0; Si — ≤ 0.8; Mn — 1.0–2.0; Ni — 9.0–11.0; S — up to 0.02; P — up to 0.035 wt.% + TiB_2 + CrB_2) and Ni-clad boron carbide B_4C. Here, the surfacing conditions varied within the following ranges: radiation power 0.9–3.0 kW, surfacing rate 0.1–0.6 m/min, focusing spot size in the direction of surfacing 1–5 mm, powder consumption 0.1–0.5 g/s. After surfacing, the microstructure of the deposited samples was examined and the nature and distribution of cracks were studied. In parallel, the residual stresses were determined using X-ray $\sin^2\psi$-method at a layer-by-layer etching. The strength of welding deposited and parent metal was evaluated on special samples using method of pins in the rupture test machine.

It was established that when the powder is fed behind the laser beam (to the weld pool tail) the energy consumption for surfacing is lower by 25–30 %, than when the powder is fed ahead the beam. In addition, the losses of the filler powder are decreased by 10–15 % and also the probability of appearance of

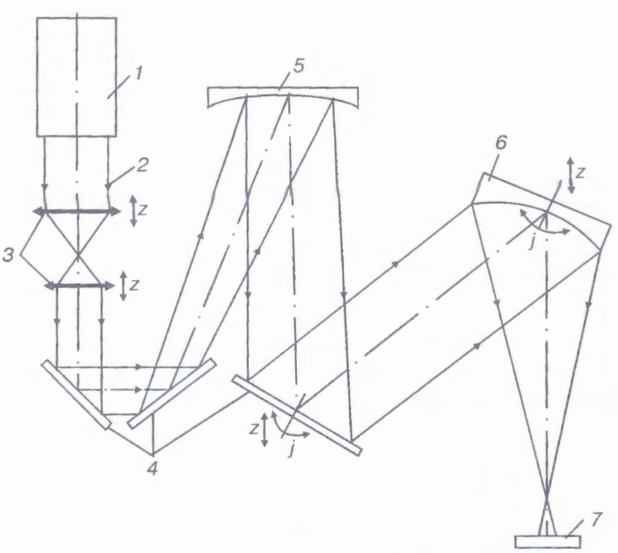

Figure 6. Scheme of laser beam focusing for producing different distribution of radiation power in treatment plane (for designations see the text)

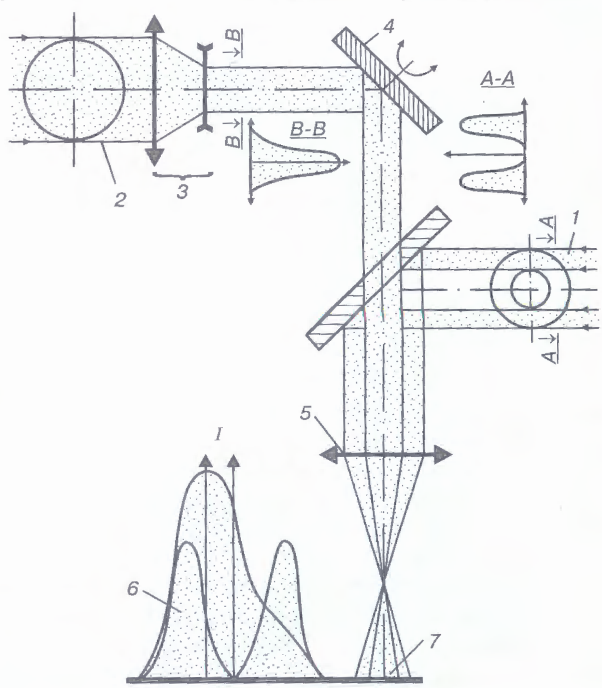

Figure 7. Scheme of system of focusing two laser beams for producing different radiation power distribution in the treatment plane (for designations see the text)

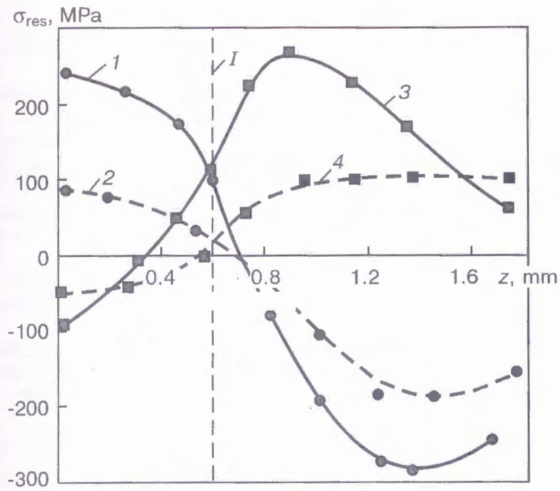

Figure 8. Distribution of residual stresses σ_{res} in depth of the deposited layer depending on the type of the material surfaced (*1, 2* – PG-SR4; *3, 4* – KhTN) and nature of radiation power distribution (*1, 3* – non-profiled beam; *2, 4* – profiled); vertical dash line is fusion boundary

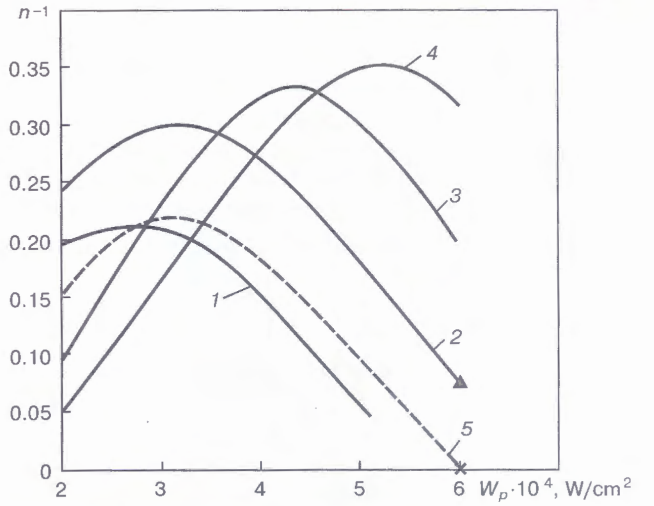

Figure 9. Effect of density of laser radiation power W_p on the specific quantity of cracks n^{-1} in the deposited layer of powder of alloy PS-12NVK at different surfacing speed: *1* – 2.0; *2* – 1.5; *3* – 1.0; *4* – 0.5 (non-profiled beam); *5* – 1.0 m/min (profiled beam)

lack of fusion is reduced. Therefore, the first scheme of surfacing was accepted as basic in this work.

The sizes of the deposited layers depend on the surfacing conditions, powder consumption and its composition. When the powders from self-fluxing alloy PG-SR4 and mixture PS-12NVK are used the width of the deposited beads is decreased smoothly with increase in the surfacing speed and density of the radiation power. In addition, the hardness of metal of the deposited layer is changed negligibly (in the range of *HV* 700–900) depending on the surfacing speed, while a quantity of cracks is changed remarkably: the higher density of the radiation power and surfacing speed, the larger quantity of the cracks. By the nature of their dislocation, the conclusion was made that the cracks are initiated in a surface layer at low speeds of surfacing and in the fusion zone at high speeds of surfacing.

Level and nature of distribution of the residual stresses are used as characteristics of quality of the deposited layer. As is seen from Figure 8 the tensile residual stresses are formed on the surface of the deposited layer from alloy PG-SR4, which can reach 70–250 MPa depending on the nature of radiation power distribution. At the fusion boundary the tensile stresses are transformed into compressive stresses of almost the same level. The different situation is observed at the surface of the layer deposited with a powder of master alloy KhTN. The residual compressive stresses, equal to 50–100 MPa, are formed which are transformed into tensile stresses in the parent metal. The use of the laser beam with a non-uniform distribution of radiation power in the focusing spot leads to the reduction of the level of residual stresses in layers deposited with both materials.

The effect of level and nature of distribution of density of the laser radiation power and also the surfacing speed on the process of crack formation in the deposited layer of alloy PS-12NVK was evaluated (Figure 9). The susceptibility of the deposited metal to the crack formation was evaluated in relative units (from the amount of cracks in the weld of 10 m length). There is its own peak of power density for each speed of surfacing, corresponding to maximum of cracks in the deposited metal (Figure 9, curves *1–4*). At similar power density and speed of surfacing (Figure 9, curves *3* and *5*) the use of the laser beam with a non-uniform distribution of power reduces the susceptibility of the deposited metal to cracks.

Strength of joints of the deposited and parent metal was evaluated from the value of a tensile rupture strength of the samples-pins of 5 mm diameter. The results obtained show that, when the lack of fusion is not observed, the strength of joints in laser surfacing is varied in the range of 250–350 MPa depending on the type of material being surfaced, i.e. it is at the same level with the strength of joints made by other methods of surfacing.

The results obtained during investigations can be used in the solution of the definite technical problems, in particular, in the improvement of the wear-resistance of shrouds of blades of gas turbine engines and drilling bits, manufacture of thrust bearings of turbines of the system of turbo-supercharging of diesel engines, etc.

CONCLUSIONS

1. The good quality of the deposited layers is provided within the following range of the laser process parameters: radiation power 0.9–3.0 kW, focusing spot 1–5 mm, surfacing speed 0.1–0.6 m/min, consumption of filler powder 0.1–0.5 g/s. In addition, the direction of powder feeding behind the beam is more economical by 25–30 % as to the energy consumption and by 10–15 % when the powder material is fed opposite the beam (at laser radiation power up to 2 kW).

2. Distribution of radiation power in the focusing spot with a shifted maximum of intensity in the direction of laser beam movement leads to a significant reduction of residual stresses in the deposited layer and decreases the susceptibility of the deposited metal to the crack formation.

3. The technological complex which uses two lasers with similar distributions of intensity of radiation in output beams makes it possible to widen greatly the technological capabilities of equipment at the expense of increase in power of a total radiation and changing the nature of its distribution at the treatment surface, to reduce to minimum the probability of failure of the production task when one of the radiators is coming out of order.

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METHODS OF DESIGNING DEVICES FOR HELIOWELDING

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ABSTRACT

The peculiarities of designing devices for heliowelding are considered. The classification of methods of designing devices of the mentioned class, including the direct transformation of solar energy, indirect transformation based on using different types of transducers, as well as combined transformation, is presented. It is shown that the indirect methods on the base of the photoelectric transducers are most promising at present. The description of a solar battery on the base of modules of the BFK-8-18 type is given. A schematic diagram of the welding installation is described, in which lead-acid cells, supplying a resonance transducer, are used as an intermediate accumulator of energy.

Key words: heliowelding, solar battery, photoelectric transducer, resonance arc welding, inverter, storage battery

The attempts of using solar energy for welding and other related technologies were made many years ago [1–4]. To serve as a technological source of the heat energy, the natural light flux should be concentrated to the required sizes and channeled into the zone of welding. These are so-called direct methods of heliowelding (HW), when the solar energy is used directly for welding without any conversions. The universal solar furnaces found the widest spreading [5]. The Sun tracking in these devices is realized with the help of a heliostat (flat mirror). The beam, reflected from it, is directed to a concentrator. The latter is usually made fixed and has a shape of a paraboloid. A technological module with a workpiece being welded is placed in its focal plane. The displacement of the workpiece and butt tracking are realized by a unit of automation, whose main function is to provide a constant size of a focal spot on the workpiece. For example, using the furnace USP-1.5, the producing of 1100 W/cm^2 density of energy flux in spot is guaranteed at the input flow of 670 W/m^2 density and coefficient of concentration $k = 4.35\ cm^{-2}$, that is quite sufficient for welding plates up to 2 mm thickness.

As the results of experiments, carried out by N.N. Rykalin and others [2] on samples of steel 12Kh18N10T (C — ≤ 0.12; Cr — 17.0–19.0; Si — ≤ 0.8; Mn — 1.0–2.0; Ni — 9.0–11.0; S — up to 0.02; P — up to 0.035 wt.%), showed, this method of welding provides high mechanical properties of welded joints and can be used for the manufacture of structures operating at static loads.

The direct methods of HW can be also realized on the base of devices with a use of mirrors and objectives. One of these devices is a helio installation «Luch-1» [3], which includes a parabolic counterreflector (Mersen's optical scheme) which directs flux of the radiant energy into the zone of welding. As to the devices which use objectives as concentrators, then they are not used in principle, because their sizes (diameter) are rather large (1.2–2.0 m) for the flux of a radiant energy, even of a negligible density. These devices are too large and expensive.

The drawbacks of the direct methods of use of the beam energy are as follows: dependence of their functioning on the weather and time conditions; complexity in adjustment of technological conditions; impossibility of generation of powerful pulsed conditions during short periods of time.

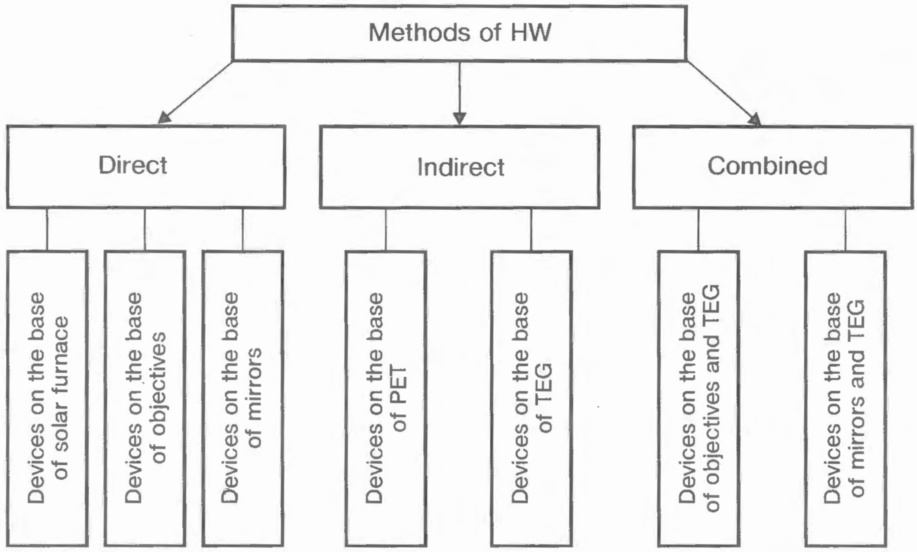

Figure 1. Classification of HW methods

There is no above-mentioned drawbacks in the devices made on the base of the indirect methods of HW. These devices are based on the procedure of an intermediate accumulation of the electric energy. The photoelectric transducers (PET) [6] or thermoelectric generators (TEG) [7, 8] are used usually as primary sources which convert the radiant energy of flux into electric energy.

There is a number of combined methods of conversion of the energy of the solar light into the electric energy which envisage the use of PET and TEG in combination with optical concentrators [6, 7, 9, 10]. Here, the energy, stored in a battery, can be used for different technological operations (welding, cutting, surfacing, etc.) [11].

The most well-known methods provide a direct conversion of a concentrated solar energy using single-type PET [6, 7], system of different-type PET, cascade-connected [6–11], or combination of PET and TEG using a spectral division of a light flux [10]. The optical concentrators used in these systems can be divided into stationary concentrators with a fixed orientation and those with means of the Sun tracking [11]. A large interest to the solar energy systems with concentrators should be noted. The comprehensive information on this subject is presented in [10].

However, the significant drawback of the concentration systems is their too large size, inconvenience in transportation, complexity in providing reliable operation of the servosystems, inevitable losses in light reflection, and also the fact that the energy of the dissipated light, amounting to 10–15 % of the total light flux, is not used. In this connection, the flat panels of solar photoelectric generators for the creation of mobile self-contained power complexes are more preferable.

The above-described HW methods can be classified in accordance with their features, as it was made in Figure 1. If the direct methods of HW use a light beam directly as a heat source, then the indirect and combined methods use the conversion of the energy flux. The later two approaches are more versatile, because, when the appropriate welding transducers, supplied from accumulators, are created, it is possible to realize almost any technological processes: arc welding (TIG, MIG/MAG), electron beam and laser welding, etc.

It is evident, that the traditional optical systems (objectives, mirrors), with the help of which the direct methods of HW are realized, are not suitable for the creation of small-sized mobile, quickly deployed welding devices. Moreover, these devices operate in real time, and, consequently, the power of the light flux in the spot depends on the atmosphere condition. To provide stability of the technological process of welding it is necessary to use rather complex devices of a tracking diaphragming, which also limit the power characteristics.

The approaches, based on the use of semiconductor PET of solar energy (solar batteries) are more promising. During recent years a significant progress was achieved in this field for the increase of the efficiency factor and improvement of mass-dimensional parameters. These elements are convenient as a charging devices for any intermediate accumulator of the electrical energy (accumulators or molecular capacitors). Let us give one of possible variants of a practical realization of this approach (Figure 2). The illustrated schematic diagram of a mobile self-contained welding complex with a self-contained power sources includes four main units: a solar battery (*SolB*), a charging controller (*ChC*), two storage batteries (*SB*) and a resonance welding transducer.

The solar battery consists of ten separate modules BFK-18-18, whose technical characteristic is given below.

Technical characteristic of module BFK-18-18

Peak power, W, not less than	18
Number of phototransducers, pcs, not less than	36
Type of design	frame
Operating current, A, not less than	1
Operating voltage, V, not less than	18

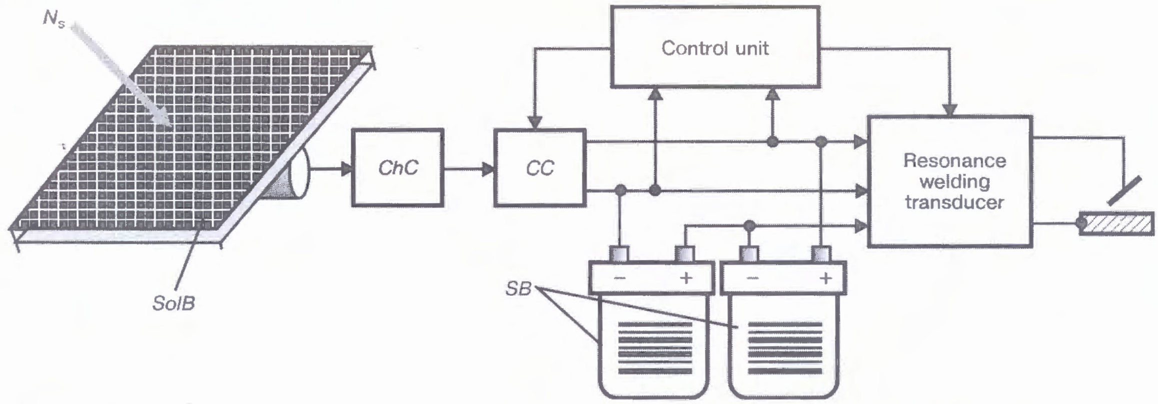

Figure 2. Schematic diagram of mobile self-contained welding complex on the base of a solar battery (see designations in text)

Dimensions, mm, not more than	20×241×749
Mass, kg, not more than	1.5
Area, m^2, not more than	0.18
Energy efficiency (by area), W/m^2, not less than	125.9
Energy efficiency (by mass), W/kg, not less than	12.9

Using the developments in the field of the space engineering, the solar modules were created, which are characterized by good energy-mass parameters at a high reliability and effectiveness.

Below, the main technical parameters of *SolB* are given. The solar converters, included into it, are made on the basis of getter treatments with unique protective and anti-reflection coating, consisting of diamond-like films. They provide 14.2 % efficiency factor, density of short-circuit current $I_{sh.-c}$ = 33.5 mA, open-circuit voltage $U_{o.-c}$ = 0.618 V, shape factor FF = = 0.701 (in the conditions AM1.5)*.

Technical characteristics of *SolB*

Peak power, W, not less than	180
Number of modules, pcs, not less than	10
Operating current, A, not less than	5
Operating voltage, V, not less than	36
Area (in working position), m^2, not more than	1.9

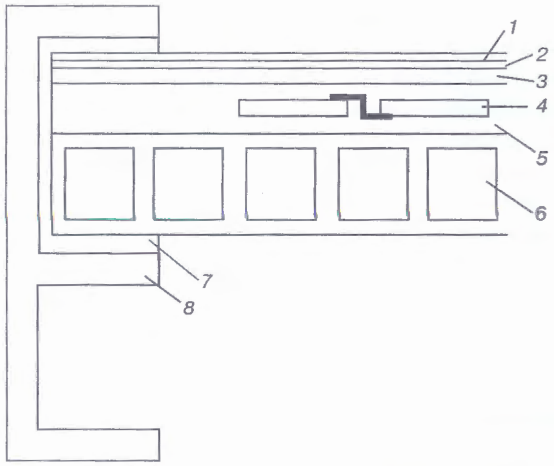

Figure 3. Design of a solar module: *1* — protective film; *2* — transparent glue; *3* — transparent plastic material; *4* — glue-sealer; *5* — photoelectric transducer; *6* — honeycomb plastic material; *7* — frame; *8* — sealer

Dimensions (in transportation position), mm, not more than	300×300×800
Mass, kg, not more than	16

Figure 3 shows a design of the module whose photoelectric transducers are glued on a honeycomb plastic frame made from a polycarbonate. From the frontal side the photoelectric transducers are closed by a sheet of a transparent plastic material which is protected by a special transparent film from the external side, thus preventing it from mechanical damages and atmospheric actions. Thus, the module design provides a complete sealing of the photoelectric transducers and their protection from the unfavourable climatic and mechanical factors. The polymeric materials and glue, which are used, are characterized by a high strength and reliability. During assembly, the module is fixed rigidly in the frame made of a light aluminium alloy. The electrical current is generated at the module rear side, on which a sealed connector is mounted.

The flux of the solar energy N_s is converted, with the help of *SolB*, into electrical signals whose power is ≈ 180 W. The energy flux, formed by a charging controller *ChC* to a required level enters, via a commutator of conditions *CC*, the *SB* and charges them up to 24 V voltage. The maximum charging current here is equal to 5 A. This is sufficient for *SB* of 90 A·h capacity. If to take into account that the allowable charge is 25 %, then it possible to use only *SB* of capacity of about 67.5 A·h for the practical realization of welding. Then, the time of welding can be determined by the following expression depending on the current:

$$t_w = w_{SB} k_{WM} / I_w,$$

where w_{SB} is the effective capacity of the accumulator; k_{WM} is the efficiency factor of the welding machine; I_w is the welding current.

Curves, reflecting this relation, are given in Figure 4. If to select the welding current equal to 100 A, then the described device at k_{WM} = 0.85 is capable to provide the 34.6 min duration of welding process in one charged cycle, and at efficiency factor of 0.60 it is 24.9 min. At 60 A current (that is sufficient for electrodes of 2.5 mm diameter), we shall obtain 57.1 and 40.7 min, respectively. If it is necessary to increase the duration of the process, then it is necessary to use

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* AM1.5 is the atmospheric mass, which is 1.5 for Kyiv.

the accumulators of the higher electrical capacity. For example, *SB* of 210 A·h capacity at $k_{WM} = 0.85$ in the discharge condition provides welding current 100 A for 75 % during 80 min that already makes it possible to deposit a sufficient amount of the electrode metal. It is shown in [10] that the mass of the deposited metal is determined by the expression

$$M_d = \alpha_d I_w t_w.$$

Product $I_w t_w$ corresponds to the effective electric capacity of *SB*, i.e. $I_w t_w = 0.75 w_{SB}$. Taking into account that the coefficient of deposition $\alpha_d = 9.5$ g/(A·h), then it is possible to deposit 1.27 kg of electrode metal using *SB* of 210 A·h capacity at 100 A current. However, if to use the welding transducer with 0.60 efficiency factor, then the mass of the deposited metal will decrease to 0.89 kg.

In this connection, the creation of the high-efficient welding equipment for the practical realization of the HW seems very actual. Investigations, carried out at the E.O. Paton Electric Welding Institute [9] showed that the resonance transducers, operating in the range of 300–600 Hz frequencies, are most suitable [12]. These devices have the efficiency factor, reaching 85 %. In the short-circuiting conditions, that are very typical of the operation of welding equipment, the consumed current in a primary circuit is decreased by 1.5–1.8 times and, here, the service life of the accumulators is increased significantly.

The schematic diagram of one of the developed and tested variants of the resonance welding source is given in Figure 5. The device represents a known scheme of a two-cycle transducer, whose frequency of commutation of transistors *T1* and *T2* is set by a controller. It is based on a microcircuit of a driver of UC3852 type. The welding transformer *Tr*, whose magnetic core is made from a high-frequency electric steel of E 3425 grade and 0.08 mm thickness, is made with a developed yoke scattering, The inductance of its scattering and reactor C_r form a series-connected resonance circuit which provides high welding-technological properties. This device is featured by that the secondary circuit consists of two similar windings w_2, w_3 which are connected from one side to the reactor C_r, and from the another side to positive and negative terminals of the appropriate accumulators via the electron keys *K1* and *K2*. Accumulators, as seen from Figure 5, operate as formers of the voltage of additional volts. The commutation of accumulators (Figure 6) occurs almost instantaneously, therefore, the voltages U_{K1} and U_{K2} are close to a rectangular shape. Windings w_2 and w_3 are phased so that the positive and negative half-waves are summed. And, as the transition of welding current through zero occurs at a high rate, the device ensures the conditions of reliable repeated arc exciting and also high stability of the welding process.

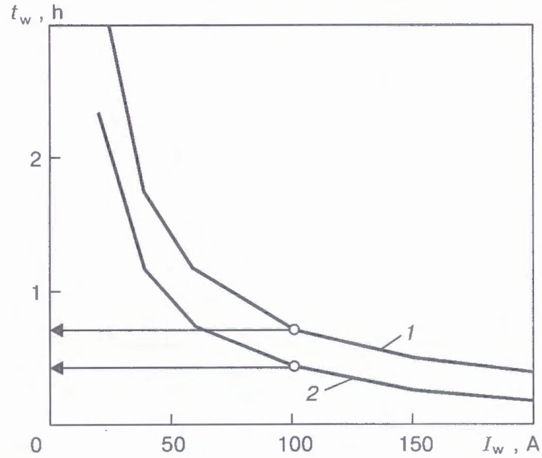

Figure 4. Dependence of time of welding t_w on current I_w for *SB* of 90 A·h capacity: *1* — $k_{WM} = 0.85$; *2* — $k_{WM} = 0.60$

For welding in all spatial positions, a modulation of welding current, realized by an electron key *K3* and additional reactor C_m is used in the device. The depth and frequency of the amplitude modulation are preset by a controller depending on the conditions and spatial position of the welded joint. Rectifier *Rect* with a voltage multiplier (*C1*, *C2* and *Choke*), mounted at the output of the resonance circuit, provide high welding-technological parameters of the device using any types of electrodes.

In the welding source, tested by us, the effective value of total voltage $U_{1,2}$ did not exceed 35 V in the idle condition. Here, the maximum welding current was 150 A. The main relations which describe the voltages, acting in the device, are as follows:

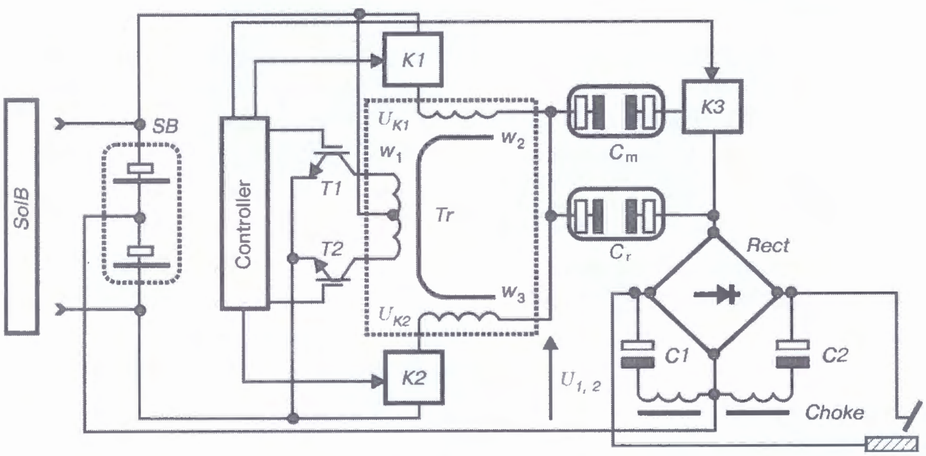

Figure 5. Schematic diagram of the resonance welding source with a rectifier and current modulation (see designations in text)

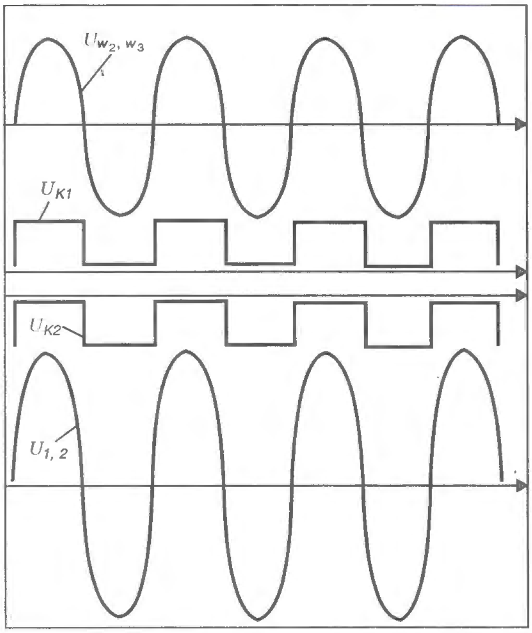

Figure 6. Time diagrams of the resonance welding source (see designations in text)

$$U_{\omega 2,\, \omega 3} = U_{2m} \sin \omega t, \qquad (1)$$

$$U_{SB} = U_{1,\, 2} \operatorname{sgn} t, \qquad (2)$$

$$U_{1,\, 2} = U_{\omega 2,\, \omega 3} + U_{SB} = U_{2m} \sin \omega t + U_{1,\, 2} \operatorname{sgn} t, \quad (3)$$

where $U_{\omega 2,\, \omega 3}$ is the voltage at secondary windings of Tr; U_{2m} is the amplitude value of voltage of secondary windings; U_{SB} is the voltage at accumulators; sgn t is the sign function; $\omega = 2\pi f$ is the transformation frequency (f = 400 Hz).

Technical characteristics of mobile self-contained electric welding complex

Dimensions (without *SolB*), mm, not more than	370×500×600
Mass (including *SolB*), kg, not more than	36
Type of *SB*	lead-acid, sealed
Capacity of *SB*, A·h, not less than	90
Service life, years, not less than	5
Time of operation from *SB* (at 2.5 mm electrode diameter), h, not less than	0.6
Maximum discharge current, A, not more than	100
Maximum charge current, A, not more than	5
Output voltage, V, not less than	32

The appearance of complex for HW is given in Figure 7.

It can be noted in conclusion that the power capabilities of the equipment for HW based on using *SolB* can be increased significantly. Thus, for *SolB* of 3 m^2 area, providing the charge current up to 19 A, it is possible to use the accumulators of 210 A·h capacity. The latter can provide I_w = 200 and 250 A during 40 and 32 min, respectively.

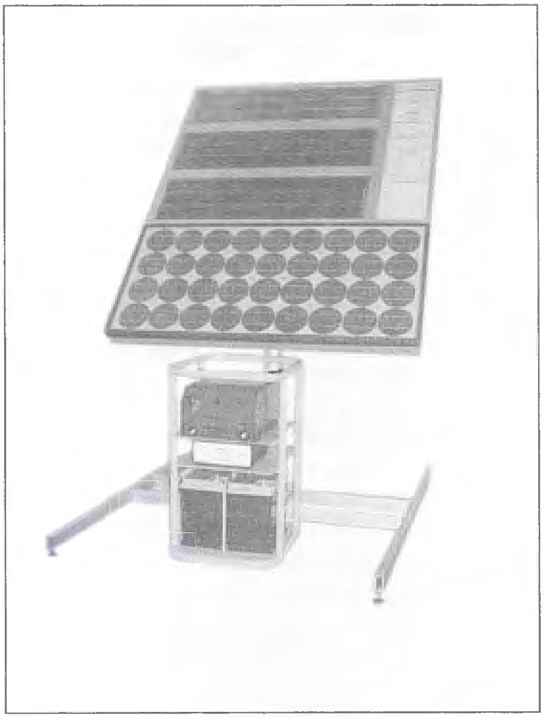

Figure 7. Complex for HW

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LASER TECHNOLOGIES FOR MODERN PRODUCTION

Russian-Bulgarian Lasertekh Ltd. Joint Venture performs delivery of laser processing complexes (LPC) of Hebr family, their mounting and repair, as well as training technical personnel for their maintenance.

LPC are fitted with 1.3 and 2.5 kW CO_2-laser sources and are applied for cutting, welding and heat treatment.

Our company has supplied several dozens of LPC to enterprises in various industries, including Tulsky Kombajnovy Zavod OJSC, Tverskoj Ekskavator OJSC, Kirovsky Zavod OJSC, Izhorskiye Zavody OJSC, etc. The experts of the company's service team have been certified by the LPC manufacturer — Optical Technologies Company, Bulgaria, and have ten years' experience of working with the above equipment. Availability of modern diagnostic equipment and specialised test benches allows any technological problems, related to Herb LPC, to be solved promptly and efficiently.

Lasertekh Ltd. JV has upgraded the system for entering control programs into NPC by substituting PC for the card photoelectric readers, supplied by the manufacturer. Complete loading of control programs into NPC memory, or frame-by-frame data entering is provided. Capabilities of editing the ready and entering a new program, use of automated transfer in a certain sequence, modes of analysis of the viewed drawing and cutting sequence are provided.

In addition to the standard set of LPC components, our Company supplies self-sufficient systems of water cooling, co-developed with Promkholod Ltd. JV, and systems of control programs preparation, developed internally. Self-sufficient cooling system keeps the water temperature at LPC inlet in the range of (6±1)–(18±1) °C at the temperatures of boiling of 5 °C and condensation of 40 °C. An optimal temperature of cooling water at LPC inlet is maintained by a cooling unit with a closed loop, air cooling condenser and evaporator.

The system of control programs preparation consists of AutoCad modules and provides plotting the cut contour both by standard AutoCad means, and additional means for issuing cutting-in commands, processing built-in contours, and assigning the cutting sequence.

Lasertekh Ltd. JV has its own production facilities, fitted with several Hebr LPC, that fulfils local orders for laser processing of various materials. The need for such productions is due to the characteristic features of development of the majority of the modern industrial enterprises, namely small-batch manufacturing of a broad range of products. Application of laser cutting instead of stamping provides a considerable saving of time and cost of preparation for production. LPC is expensive process equipment, therefore performance of laser processing work through co-operation is cost-effective for the factories.

Lasertekh Ltd. JV was the winner of the «Russian Mark» National Competition in the nomination of services on laser processing of materials, delivery and servicing of laser complexes, and was awarded a «Russian Mark» silver sign of quality.

S.N. SMIRNOV
Director General,
Lasertekh Ltd. JV

DEVELOPMENT AND APPLICATION OF MANUAL LASERS FOR INSTALLATION WORK

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ABSTRACT

The paper deals with the applications and advantages of manual lasers, special design features of heads, depending on their purpose (welding, cutting, surface treatment). Potential for material saving, when using laser technologies, is described.

Key words: *laser processing, linear and gantry systems, robots, manual lasers, heat input, mobility*

Lasers are widely applied in practically all the fields of engineering. In addition to application in electronics, data communication modules, measurement devices for determination of speed and distance, medical systems, the laser is one of the all-purpose tools for material surface processing. This energy source allows performing welding, cutting or surface treatment. The latter is conducted using all-purpose CO_2-, Nd:YAG or diode lasers with output power from several watts to several tens of kilowatts in the majority of cases.

Linear or gantry systems or industrial robots are mostly applied for relative displacement of the item and the laser beam in laser processing of materials. Advanced developments allow scanning systems to be used.

Linear or gantry systems provide three-dimensional processing by the laser beam in the Cartesian co-ordinates (three main axles are located normal to each other). At least two pivot axles are required for orientation. The third axle can further improve the accessibility of the processing location. It is often installed co-axially with the laser beam, so as to allow sensors mounting in front, lateral feeding of the working gas or welding wire feeding in a certain direction along a tangential trajectory. In principle, linear and gantry systems can be used for cutting, welding, brazing and surface treatment. Gantry systems have a very rigid structure and high accuracy of the trajectory, respectively.

However, the advantages of laser processing of materials cannot be used in all the industries without limitation. Available integrated systems are oriented to automated manufacturing processes. This means that, firstly, the laser radiation source proper is tied to a certain point, i.e. is stationary, in the majority of the cases. Secondly, the equipment, providing the relative movement of the laser beam and the item (these mostly are multi-axes linear systems or robots with a hinged arm), is large-sized and heavy, i.e. the programming, required for processing, takes a lot of time. Therefore, this equipment is not yet used in many of the industries. Mobile manual lasers open up new areas of application.

Mobile manual laser systems are compact Nd:YAG or diode laser systems of up to several kilowatt power. Pulsed lasers or continuous-wave lasers are used, depending on the application. Manual systems (similar to stationary units) have all the advantages, inherent to the laser. Furthermore, they are mobile, i.e. not tied to one place. All the necessary functions of one system are fulfilled due to a compact mobile design; dimensions, convenient for transportation; build-in rollers, providing for easy movement; laser sources with several fiber-optic outlets to select from; air-water cooling; working gas feeding; inner control of manual processing; one or several heads for manual processing; integrated safety features.

Manual heads for welding, cutting and surface treatment allow processing individual parts, small batches and large-sized parts without involving any programming cost. This requires head designs, suitable for the posed task. MobilLaserTec heads are applied, that are comparable with manual heads used in MIG/MAG or plasma/TIG welding with the same functions and advantages, as in laser processing of materials.

The main features of the heads are as follows: no programming cost, built-in system of monitoring the process and feeding the shielding gas; provision of a crossjet for protection of the optics; ability to quickly replace the cassettes with protective glasses; compatibility with Nd:YAG lasers; implementation of com-

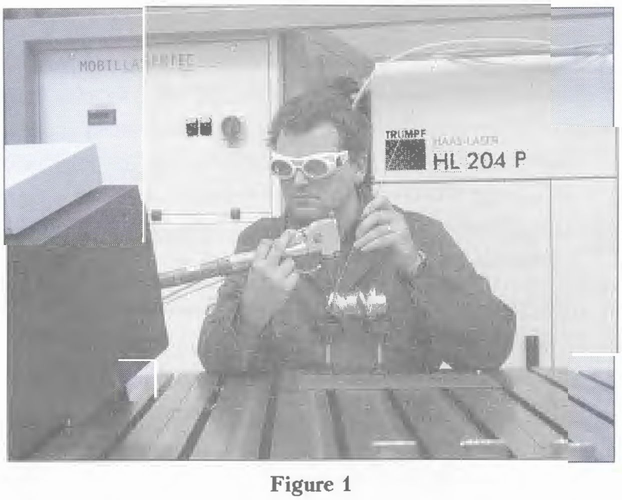

Figure 1

Figure 2

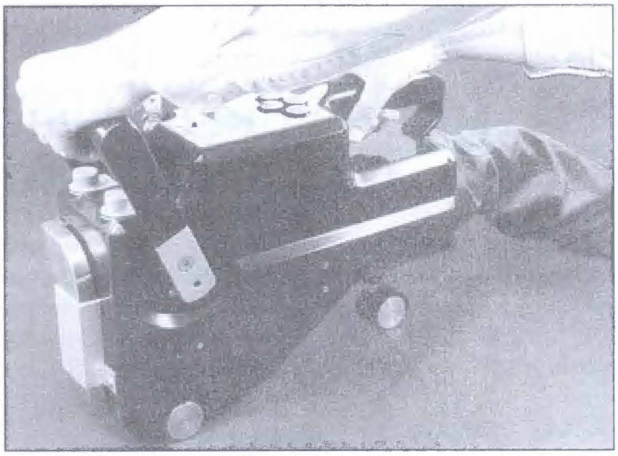

Figure 3

pact modular design; provision of laser safety due to several independent sensors.

Laser welding and cutting systems further provide: constant heat input due to a built-in feeder; ability to weld different butts; ability to adapt built-in clamping devices; ability to process difficult-of-access contours, using a swivel head.

Optimal use of mobile manual laser systems requires satisfying the following limiting conditions:

- connection to 380 V mains;
- closed vented working space with above-zero temperature for air-water cooling;
- suction;
- qualified welding personnel;
- appointment of a person in charge of laser radiation protection (two days training, materials in the package, enclosed with the integrated system);
- specified fixtures to provide laser and labour safety;
- means of operators' personal protection.

Head operation in surface treatment (Figure 1) requires providing the following conditions: Nd:YAG laser system with fiber optics of Rofin or Haas Laser Company (maximal average power P_l — 500 W; fiber plug of Haas or Rofin Company, fiber diameter of 0.3–0.6 mm); connection to 220 V mains; specified fixtures to provide laser and labour safety; appointment of a person in charge of laser radiation protection; qualified welding personnel; means of operators' personal protection.

In the case of the head operation in welding/cutting (Figure 2) the above conditions should be provided, and a laser system of maximal average power (P_l = 3000 W), should be used.

Manual or partially mechanised systems allow conducting laser processing of materials for new parts without any special cost, for instance, large-sized parts, individual elements, small batches, as well as repair work.

Laser welding has already become a regular process in fabrication of vehicle bodies. Individual samples or small batches are now made, using robots, that require considerable programming cost. Manual system can significantly reduce the scope of this work, and, hence, improve the cost-effectiveness.

Laser welding provides a better surface quality due to lower heat input. Therefore, there is no need to perform expensive flame straightening or grinding operations, taking up a considerable portion of the time, in fabrication of the rolling stock bodies. There are, however, certain limitations also in this case, associated with a small number of similar parts, dimensions of structures or typical tolerances. Rolling stock manufacturers still use very few laser systems, and even these just for cutting in the majority of cases.

Manual laser systems can be also used at minimal cost for processing stainless steels or other high-alloyed materials, for instance, in fabrication of similar parts. Automatic repair is impossible in most of the cases. Therefore, in this case also the welding operations should be performed manually. TIG welding is being more and more widely applied lately, with all its disadvantages (higher heat input and distortion, in particular, because of applying too thick layers). In manual laser welding the item geometry is close to the final contour, and distortions are minimal (Figure 3).

A laser cutting system has been extensively used in Nord power plants from the start of 2001. In the nuclear power plant in Greifswald metal shells and tanks were earlier severed by this process, unique in terms of dust generation level, which is attributable to an extremely narrow cut.

Laser systems have a considerable potential in terms of repair and maintenance of comparatively expensive forming and castings tools. Manufacturing defects are to be repaired, and it cannot be achieved without processing by manual laser tools. Laser processing is highly accurate, the coating material layer is thin, i.e. minor post-processing treatment is required. Pulsed laser allows difficult-to-weld materials to be treated without preheating. Manual servicing allows «out-patient» treatment, for instance, in the press. This brings down the cost associated with storage and tool idle time in processing, and, therefore, the possible machine downtime is essentially shortened.

Mobile manual laser systems open up new possibilities for the users. Processing that could not be done earlier, using regular lasers, can be successfully performed by mobile systems. The laser can be brought to the item, and can perform processing with a readily controllable head, without spending any time for programming. This allows the laser to be used in those areas, where it was unthinkable before.

MULTI-PURPOSE PROCESSING COMPLEXES, INCORPORATING LGT-2.01M LASERS

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ABSTRACT

The paper briefly describes the work of the Russian Welding Institute on development and improvement of processing complexes for welding and cutting low-carbon alloyed steels, brass, titanium, plastics, glass and other materials. Cases of effective application of laser technologies are presented.

Key words: *laser welding and cutting, processing complexes, assemblies, systems, positioning tables, capacity*

Processing lasers LGT-2.01M have been developed in the Russian Welding Institute, based on Lantan lasers of the Institute of Problems of Mechanics of the Russian Academy of Sciences. Fast-flowing CO_2-lasers with a longitudinal semi-self-maintained DC discharge, transverse frequency preionisation and five-pass stable cavity are well-established as the energy source for technological processes of thermal treatment of materials. Results of laboratory and industrial operation allowed defining additional requirements to the main components and systems, as well as conduct laser upgrading that essentially improved its properties. At present preionisation electrodes have been designed that feature reliability and long-term performance. A procedure of initial material selection has been developed and check of the quality of output mirror of zinc selenide has been performed in co-operation with the local manufacturers of the mirrors, allowing their service life to be extended considerably.

A fast-response electromechanical power breaker has been installed, that simultaneously is a calorimeter. It allows, if required, recording the radiation power on the plotter during the pauses in the technological process. Electronic switching of the beam was added for short-time processes and frequent change of the items being processed. The signal of preionisation frequency variation, as well as of the main discharge current and radiation power from the threshold up to the working values, is issued by the program of item processing through the optoelectronic pair. A system of the main discharge current stabilisation is incorporated, maintaining its value with up to 0.1 A accuracy in the range of currents, required for processing a group of items with close levels of radiation power.

The above measures allowed taking up development of processing complexes, based on LGT-2.01M laser. The first processing complex was mounted in Les CJSC (St.-Petersburg). It incorporated a positioning table with the work space of 1000×1000 mm, «flying» optics and computer control, that was provided by the customer. This complex is used to perform cutting of the blocks of ornamental (palace) parquet of various kinds of wood (birch, oak, beech, mahogany) 5 to 15 mm thick at the speed of 110 m/h. Control programs, developed at Les CJSC allow taking into account the cut width, which is different for different kinds of wood, thus minimising the gaps between the elements, made of different kinds of wood when assembling the blocks. The complex is kept in the operable condition without involving the Russian Welding Institute.

The processing complex for welding parts and bodies of storage batteries was mounted at Istochnik Ltd. JV NIAI (St.-Petersburg). Its focusing system is stationary, and AP-400 positioning table, rotators and manipulators are used for the processed item displacement. The complex is used for welding low-carbon alloyed steels and alloys 0.3 to 1.5 mm thick, as well as cutting shaped active elements of nickel-hydrogen accumulators, which consist of a nickel mesh base, made of 0.1 mm wire, moulded with nickel powder.

A complex for laser welding of filter bodies for fine cleaning of petrol in cars with injection engines, has been developed, manufactured and introduced for Big-Filtr Ltd. JV. It is used to perform successive welding of three circumferential welds of filter components of steel 10Kh18N10T, namely cover and sleeve, to nuts with the wall thickness of (0.4 + 3.8) mm in the welding area and 18 mm diameter and of a sleeve to cover with the wall thickness of (0.4 + + 0.4) mm and 54 mm diameter. The complex consists of LGT-2.01M laser and automated fixture, providing centering of the filter parts, their fastening, rotation and successive axial displacement, filter lifting and lowering to fix the welding area relative to the stationary focusing head. The electronic system of beam power switching ensures crater welding up. A protective air shutter and monitoring the lens overheating temperature are envisaged in the focusing head. Average life of a lens of locally-produced zinc selenide of PO-4 grade is 30,000 to 60,000 welds under these conditions.

In connection with the change of the process cycle of filter manufacturing the nuts are now welded to covers separately, then the nuts are welded to sleeves, while the cover is joined to the sleeve only after mounting into the filtering element body. All the items are checked for tightness by air pressure of up to 50 MPa at immersion into the water. The complex capacity is 6 to 10 welds per minute. The current program of filter output is fulfilled by making 45,000 to 60,000 welds per month, with the design capacity of 75,000 welds per month.

The Russian Welding Institute manufactured and is operating two complexes for laser cutting. Czech digigraphs are used as positioning tables, accommodating the «flying» optics, including two copper rotary mirrors and focusing head with a lens of zinc selenide, cutting gas feed system and nozzle that forms the gas jet. In view of the high cutting speed, idle setting motion, as well as inadmissibility of burning of the items working surface, an electronic switching circuit has been developed, which provides a drop of the laser radiation power from the working level to the adjustable safe level, in terms of the traces left on the item, and its rise in 0.01 s. The high level of the noise, generated by LGT-2.01M laser, predetermined the need to provide optoelectronic channels for transferring commands from the positioning table to the laser. In cutting small-sized thin items of dielectric materials the laser beam is first fed onto the dividing board of zinc selenide, mounted at 45° angle, and then is fed to the two synchronously moving focusing heads. The process efficiency is doubled.

Automatic cycle of the table operation is organised, where removal of processed items and mounting of the new blanks in the same working position are performed during cutting of the items in the second position, thus providing a time saving. Exhaust ventilation removes the destruction products, formed in laser cutting, thus providing for operator's comfort. The complexes are used to perform cutting of items of low-carbon and alloyed steels 1 to 5 mm thick, brass, up to 3 mm thick titanium, as well as wood, plywood, plexiglas, textiles and diverse plastics up to 20 to 40 mm thick. Even when large batches are processed the complex operates reliably for 1.0 to 1.5 shifts. The approximate life of locally produced antireflection lenses of zinc selenide at beam impact is 100 h in metal cutting and 500 h in dielectric cutting. Processing complexes, based on LGT-2.01M lasers, are successfully operating in production.

DEVICE FOR A FOCUSING LENS PROTECTION FROM SPRAYS AND HEATING IN LASER WELDING

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ABSTRACT

Analysis of different variants of existing designs of a barrel for the laser welding is given. Results on improvement of the protection of a focusing lens in CO_2-laser welding of aluminium alloys from sprays of metal vapours and its heating by the reflected beams are presented. New design solutions on manufacture of the barrel are offered taking into account the conditions of the laser welding of aluminium alloys.

Key words: *laser welding, aluminium alloys, reflected beams, barrel, lens, plasma flame*

In laser welding a nozzle head (barrel) is a final element of an optical path in the design of a set of the CO_2-laser installation, through which the laser beam is directed to the welding site. As a rule, the barrel fulfills several very important functions on which the safe and failure-free operation of the laser installation, as well as the quality of welded joints, depend. A lens (crystal KCl) is located in the barrel, focusing the laser beam and providing the required level of energy concentration in the heating spot for the metal melting. The barrel includes also a separator through which a flow of a shielding gas enters preliminary for the focusing lens cooling. The shielding gas is supplied through the nozzle at the lower section of the barrel to the welding site. Sometimes, a mechanism for a filler wire feeding to a weld pool is fastened on the barrel. In addition, different-purpose sensors can be arranged on it.

In practice, many different variants of designs of the barrel for the laser welding are used [1–7]. In each of them separate problems of improvement of the reliability of equipment service and ensurance of the required quality of the welded joints are solved. During our investigations of weldability of the aluminium alloys using the laser beam a design of a multifunctional barrel was optimized. This design included partially both the well-known and also new solutions, coming, first of all, from the specific features of welding materials of this class.

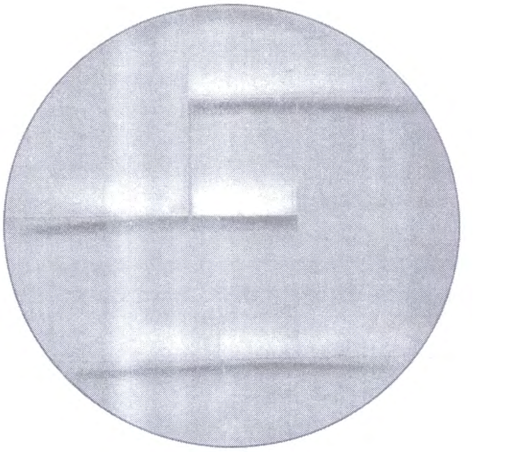

Figure 1. Typical case of a focusing lens failure under the action of thermal stresses

Several factors occurring in the process of welding aluminium alloys influence the term of service of the focusing lens. As the coefficient of reflection of light beams by the aluminium surface reaches 0.97, then the higher power of the laser beam, used for welding, the higher heating of the lens with beams, reflected from the weld pool surface. If the welding of short joints is performed, then the lens heating with reflected beams is negligible and there is no hazard of its coming out of order. If the welds of length of several meters are welded, the temperature drop occurs in the lens in the direction of its radius and it can crack or fail. Figure 1 gives an example of «thermal» fail of the lens (crystal KCl) of 80 mm diameter.

The lens heating with a heat radiation, whose sources in welding aluminium alloys are an ionized plasma, forming in a penetration channel, and also the surface of the weld pool molten metal, is not less hazardous.

And finally, the lens is heated greatly by the effect of process of evaporation of alloying elements from the aluminium alloys being welded. Such alloying elements, as zinc, magnesium and lithium, have a high pressure of vapours and, therefore, their losses in welding for evaporation are, sometimes, significant. The negative effect of the vapour flow is not only due to a high heat storage. Having condensed on the lens surface, the metal vapours reduce its transmissivity of the light beam which is retarded in a condensate layer of the metal vapour and losses a part of its energy for the lens heating.

The investigations were carried out using the laser equipment LT-104 with the 10 kW maximum power of the beam. To reduce the negative effect of the plasma flame on the lens, which is coming from the penetration channel, a scheme of its blowing away with a shielding gas through the nozzles, arranged ahead of the weld pool, was developed. The optimizing of nozzles and selection of effective parameters of

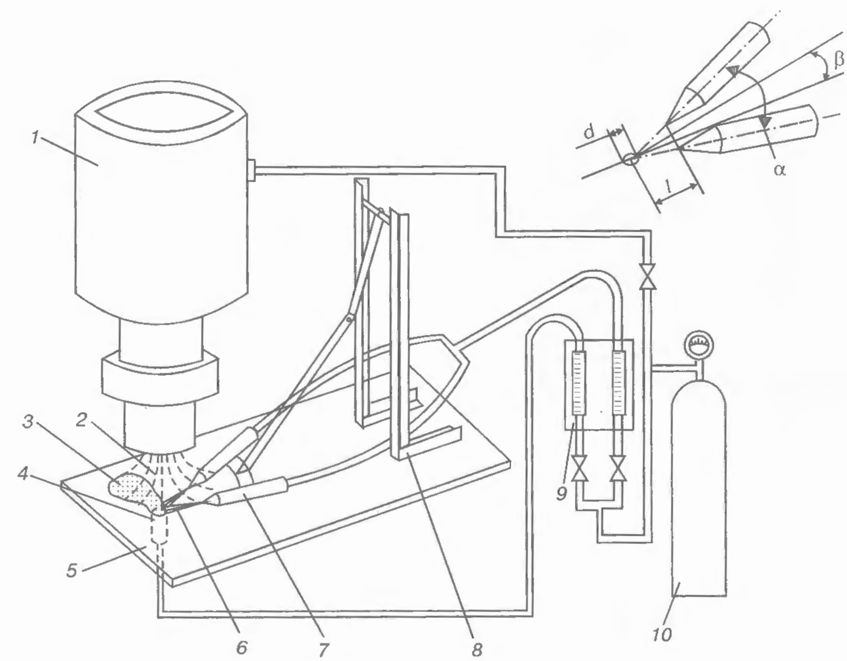

Figure 2. Scheme of laboratory bench for investigation of interaction of flows of shielding gas, blowing out jets and plasma flame from the penetration channel: *1* — cylindrical barrel for shielding gas supply; *2* — flow of shielding gas; *3* — smoke cloud-simulator of a plasma flame; *4* — simulator of the penetration cavity; *5* — simulator of sample being welded; *6* — jets of blowing out gas; *7* — nozzles for supply of the gas deviating the plasma flame; *8* — support; *9* — flow meters for gas consumption control; *10* — cylinder with a shielding gas (*d* — cavity diameter; *l* — distance from nozzles of blowing out gas to the cavity; α — angle between the blowing out nozzles; β — angle of inclination of blowing out nozzles to the plane of sample being welded)

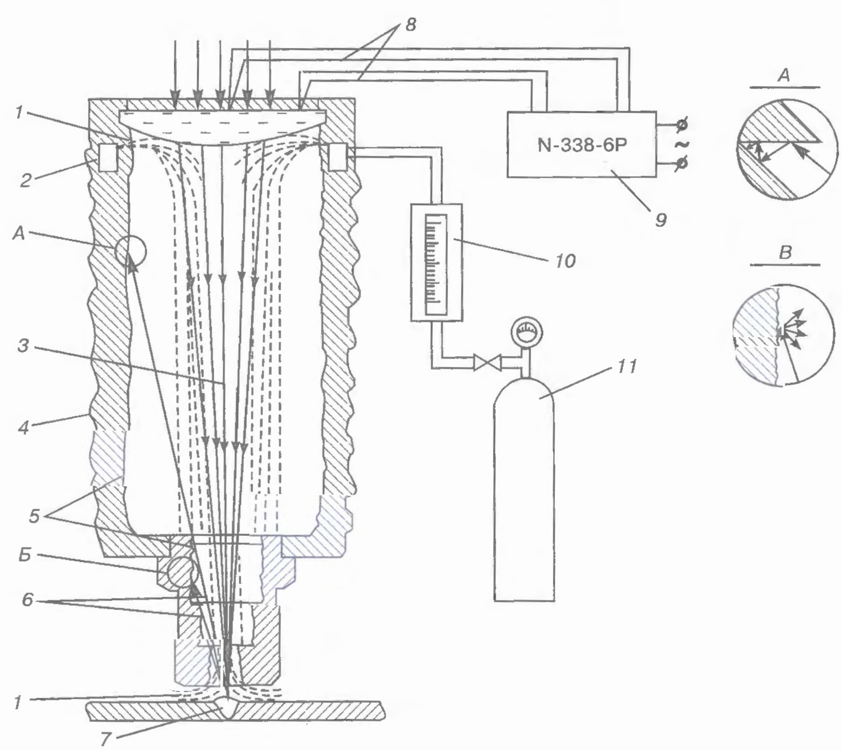

Figure 3. Scheme of a barrel for lens fixation and its protection from the flow of metal vapours and reflected light beams: *1* — flow of gas for shielding and cooling of the lens; *2* — circular cavity for supply and separation of the shielding gas; *3* — focused laser beam; *4* — external heat dissipating surface of the barrel; *5* — internal light-absorbing surface of the barrel; *6* — reflected light flow; *7* — weld pool of molten metal and channel of penetration; *8* — thermocouples for control of lens heating; *9* — instrument for recording temperature of the focusing lens; *10* — flow meter of gas consumption control; *11* — cylinder with a shielding gas (*A* — profile of treatment of the barrel light-reflecting surface; *B* — profile of treatment of the nozzle light-dissipating surface)

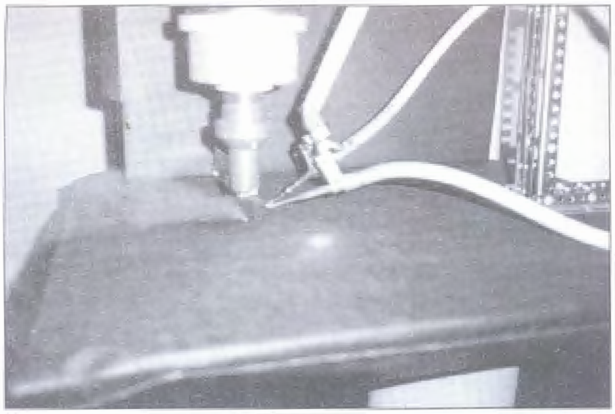

Figure 4. Bench tests of a barrel of the new design

blowing away were tested at the laboratory bench (Figure 2).

During experiments, the necessary use of two nozzles was established, because one nozzle does not provide a sufficient reliability in the plasma flame blowing away. For the most effective blowing away, the angle α between nozzles is set equal to 40–50°. For angle β between nozzles and surface of plates being welded, the best results were obtained in the range of 30–40°. At lower values the blowing away does not take place. With increase in angle β for more than 40° the risk of violation of the pool dynamics by a gas flow is appeared. With allowance for optimizing the spatial position of the nozzles, the optimum values of diameters of outlet orifices are within 0.5–0.8 mm.

To protect the lens from the effect of reflected beams of the light flow and heat radiation, a design of a barrel was made so that to provide a step changing of its diameter, i.e. 6–8 mm from the outlet orifice up to 85 mm in the place of lens fixation. The inner surface of the barrel had a special profile (Figure 3, view *A*, *B*), promoting the dissipation and reflection in a reverse direction of radiation reflected from the pool surface. To eliminate the barrel heating, its external surface was made developed (Figure 3).

Lens protection from the vapour flow was realized by a collector, located directly under the lens. The shielding gas in the form of many jets is supplied from the collectors through a large quantity of holes made in a radial direction. After washing the lens surface and its cooling the shielding gas is directed towards the vapour flow to the outlet orifice of the barrel. Figure 4 shows a moment of laboratory testing of the barrel of the new design. To visualize the behaviour of the plasma flame coming from the channel of penetration during welding, an intensive stream of smoke was used. It was supplied under the excessive pressure in the direction opposite to the shielding gas from the barrel nozzle.

After the laboratory tests the optimized variant of the barrel design was used during investigation of weldability of aluminium alloys of different systems of alloying.

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