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FEATURES OF WELDING HIGH-STRENGTH ALLOYS BASED ON ALUMINIUM AND BERYLLIUM USING HIGHLY-CONCENTRATED HEAT SOURCES (REVIEW)

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ABSTRACT

Results of welding a wide range of light alloys by highly-concentrated heat sources have been analyzed. It is shown that the characteristic defects are hot cracks, internal pores, HAZ softening, weld sagging, undercuts and irregular reinforcement bead formation. It was found that in order to produce sound joints, it is necessary to thoroughly select welding mode parameters, remove the oxide film from blank edges before welding, ensure reliable protection of the weld pool, and in some cases and it is rational to apply preheating or concurrent heating. One of the advanced methods to minimize the susceptibility to formation of the above-mentioned defects is application of hybrid laser-arc and laser-plasma welding processes. The welds produced by electron beam and laser (CO_2- and fiber-optic lasers) welding processes are quite similar visually, by their macrostructure, as well as the main characteristics. The weld strength parameters and heat input required for full penetration of the metal are somewhat different for different welding methods (for fiberoptic laser it is usually 30 % less).

KEYWORDS: welding, laser, electron beam, laser-arc, laser-plasma, light alloys, aluminium, beryllium, defects, mode parameters, mechanical properties

INTRODUCTION

Aluminium, magnesium, beryllium as well as their alloys are widely used in modern equipment manufacture in particular in aircraft and rocket construction that is caused by unique combination of the next properties, namely low density at high values of specific strength, corrosion resistance and thermal conductivity. Variety of structures from these materials as well as tendency of welded joints to defect formation requires searching the new methods of welding of indicated alloys. High thermal conductivity complicates development of classical arc welding technologies of these alloys. One of the radical methods of decrease of thermal conductivity effect on residual stress-strain state of welded structures is application of highly-concentrated heat sources, in particular, laser, laser-arc, laser-plasma and electron beam. Welding with such highly-concentrated heat sources allows reaching high indices of efficiency, quality of produced joints, has high stability and good repeatability of results. Nevertheless, the literature has got the information about effect of parameters of modes and conditions of welding process on formation of welded joints, their tendency to defect formation doesn't always match, therefore investigations of peculiarities of production of joints of light alloys based on aluminium and beryllium using highly-concentrated energy sources is relevant.

PROBLEM STATEMENT

One of the main problems of laser welding of light alloys is high reflectivity of the material being joined or its low absorption coefficient of laser radiation, which makes up to 10 % for wave length 1.06 μm [1]. This promotes decrease of efficiency of the process of laser welding. Moreover, the processes of welding using highly-concentrated heat sources are complicated due to high values of thermal conductivity of these alloys: 236 W/(m·K) for aluminium and 201 W/(m·K) for beryllium under normal conditions [2]. One more problem is a presence of thermodynamically stable oxide film (Al_2O_3 or BeO) on welded surfaces, coming of which into a cast weld metal results in its mechanical weakening [3]. On their own light alloys are very sensitive to effect of environment, susceptible to formation in welds of oxide inclusions and pores at interaction with air atmosphere [4].

Metallurgical processes of welding using highly-concentrated energy sources of light alloys differ with presence of keyhole, intensity of evaporation of alloying elements as well as peculiarities of solidification under conditions of effect of welding thermal cycle. Laser and hybrid processes additionally require consideration of base metal interaction with environment gases. Practical realization of the processes of welding of light alloys using highly-concentrated heat sources is related with a series of peculiarities that reflect on technology, selection of method and modes as well as properties of produced welded joints.

An aim of this work is review of the modern achievements in the field of welding with highly-concentrated heat sources of light alloys based on aluminium and beryllium, which are used in aircraft, rocket and space engineering, determination of the main peculiarities of welding processes and ways of removal of the typical disadvantages.

In order to reach the aim we have analyzed the peculiarities of the processes of welding using highly-concentrated heat sources of light alloys based on aluminium and beryllium; outlined the main general peculiarities of welding and physical modeling of a process of welding using highly-concentrated heat sources of light alloys that are characterized with unsatisfactory technological ability to welding.

ANALYSIS OF PECULIARITIES OF WELDING USING HIGHLY-CONCENTRATED HEAT SOURCES OF LIGHT ALLOYS BASED ON ALUMINIUM AND BERYLLIUM

Due to high mechanical properties an issue of welding of high-strength aluminium alloys of Al–Mg–Si (series 6xxx) [5], Al–Zn–Mg–Cu (series 7xxx) as well as aluminium alloys doped with lithium (Al–Mg–Li system) and scandium (Al–Cu–Li–Sc) [7] is of high interest in modern industry. First of all, three component Lockalloys of Al–Be–Mg system of Lx-59-3 grades (59Be, 3Mg), Lx-40-3 (40Be, 3Mg) [8] are referred to widely used high-strength beryllium alloys. The main mechanical properties of the most widespread light alloys are given in Table 1. It is noted that welding of such alloys is complicated due to their susceptibility to formation of hot cracks and pores.

In contrast to electron beam welding [9] development of welding technology with laser radiation requires thorough weld shielding from environment [10]. In case of welding of light alloys such gases as helium, argon as well as their mixtures are used. From point of view of shieldinging the gases with high ionizing potential are relevant for usage in a zone of action of laser radiation. The following scheme of gas shielding of weld in laser welding is recommended [11]: shielding of weld pool and weld surface by helium with 8–10 l/min consumption and weld root by argon with 5–8 l/min consumption. A peculiarity of such gas shielding is abrupt increase of penetration depth after overcoming primary boundary values of radiation energy. At hybrid consumable electrode laser-arc welding for minimizing pore formation and increase of penetration depth it is recommended to add 50 % of helium to argon shieldinging gas [12].

In addition to gas shielding, for laser [13] and laser-arc [14] welding it is possible to use a flux protection of a surface and weld root. Before welding the surface of joint and its root part is covered with specially developed fluxes. Application of flux protection allows reducing the requirements to preliminary joint assembly increasing the possible gap between welding edges by 2–3 times [15]. The fluxes may contain graphite, metal powders, fluorides of alkali and alkaline earth metals. Such materials promote increase of an absorption coefficient of laser radiation, improve surface activity of melt, provide high coefficient of surface tension of flux melt. Application of fluxes for laser and hybrid welding of light alloys results in redistribution of energy balance that is related with increase of absorption of radiation energy and removal of oxide film. At that efficiency of the process rises, limit of critical density of power typical for laser welding of light alloys is reduced.

Flux protection in contrast to gas one provides smooth increase of penetration depth at rise of energy input.

As a rule, weldability of light alloys with highly-concentrated heat sources is similar to their weldability using traditional arc sources. Table 2 gives the data on aluminium alloy weldability.

One of the most important aspects of the specifics of aluminium and beryllium alloy welding is the difference in melting temperatures and absorption coefficients of the metals proper and their oxide films. Aluminium and beryllium are susceptible to intensive oxidation at temperatures exceeding melting temperature. Oxide film has high melting temperature (> 2000–2500 °C) and does not melt in the process of welding, however can partially burn out due to intensive absorption of laser radiation. This film is characterized with high adsorption capacity

Table 1. Main physicomechanical characteristics of some aluminium and beryllium–aluminium alloys (at normal temperature) [5, 6, 8]

Alloy grade	Yield limit, MPa	Strength limit, MPa	Relative elongation, %	Young modulus, GPa	Density, kg/m^3	Hardness *HB*, MPa
5083	130–160	200–280	15	69	2720	70
6061	145–276	240–310	9–14	69–70	2700	65–95
7005	245–290	355–400	8–12	72	2770	90–95
7075	450–500	510–570	3–11	71,7	2810	150–160
Lx-59-3	280–480	220–490	1–9	175–200	2100	250
Lx-40-3	350–490	250–530	1–9	180–200	2100	250

Table 2. Weldability of aluminium alloys [16]

Alloy series	Application	Weldability	Exceptions	Filler alloy
1xxx	Commercially pure aluminium (A1 > 99 %). Electric current conductors, products with high corrosion resistance etc.	Easy to weld	No	Mostly 1100
2xxx	High-strength aerospace aluminium alloys (“durals”) are mostly used in form of plates and sheets	Mostly not weldable due to high tendency to hot cracking	Alloys 2219 and 2519 are welded	2319 or 4043
3xxx	Medium strength aluminium alloys can be easily subjected to forming. Used for heat exchangers and air conditioning	Easy to weld	No	4043 or 5356
4xxx	Used for structures and as alloys for welding and brazing	–»–	–»–	4043
5xxx	Mainly for high-strength sheets and plates	–»–	5183 or 5556 are used for welding of 5083	5356
6xxx	For pressed profiles, sheets and plates etc.	Good weldability at corresponding technology	Susceptible to hot cracking	4034, 5356
7xxx	High-strength aerospace alloys	Mostly unweldable due to tendency to hot cracking and corrosion under mechanical stress effect	Welded are alloys 7003 and 7005 for pressed profiles and alloy 7039 for sheets	5356

to gases and water vapor that results in appearance gases, pores and various inhomogeneities in the weld pool [3]. The film particles can enter into the weld pool forming oxide inclusions in the welds that decreases mechanical properties of the welded joints. Therefore, special methods are used in laser and hybrid welding. They promote destruction and removal of the oxide film and metal protection from reoxidation — from preliminary mechanical removal to laser burning [17].

The main difference of laser welding of light alloys is a threshold nature of penetration which starts only after reaching a specific level of power density (about 10^6 W/cm^2) [15]. It is explained by combination of the coefficients of reflection, thermal conductivity and heat capacity of aluminium and beryllium alloys. At introduction of sufficient amount of energy after the start of melting process the coefficient of reflection rapidly decreases and intensive penetration of metal with formation of a keyhole takes place. Power density threshold depends on radiation wave length, focusing parameters, welding rate, thickness and condition of plate surface as well as material composition. It can be significantly reduced at hybrid welding as a result of effect of arc or plasma constituent of the process [18].

Presence of threshold level of laser radiation power, which provides penetration in welding, makes accurate selection of mode parameters very relevant. Thus, authors of work [15] determined that for alloy 1560 (analog 5083) power of CO_2 laser at 2.0–2.2 kW level provides penetration depth about 1.5–2.0 mm. Penetration radiation is virtually absent at lower power due to the reason of high reflection coefficient mentioned above. Further increase of radiation power results in virtually linear increase of penetration depth.

Today fiber lasers [19] are recognized as the most perspective ones. Nevertheless, their application can result in such problems of weld root formation quality as nonstable penetration, melt splashing and nonuniformity [20]. This is related with the rise of pressure on pool bottom (keyhole effect) when using fiber laser instead of CO_2 laser. Therefore, it is necessary to carry out the investigations on welding of light alloys with fiber laser.

For investigations on welding with fiber laser in work [15] there was used a complex based on fiber ytterbium laser of IPE-Polyus Company LZ-3.5 of 3.5 kW power. The investigations showed that the level of power density, necessary for start of penetration when using fiber laser is approximately 2 times lower than for CO_2 laser (Figure 1). It can be seen from Table 3, which provides the modes of welding of aluminium alloy 01570 (AlMg6Mn0.5Sc3) of Al–Mg–Sc system with fiber and CO_2 lasers, that power of laser radiation necessary for 2.0 mm thick sheet welding using fiber laser is 30 % lower than in welding with CO_2 laser. It should be noted that similar alloy is sufficiently well welded using electron beam method [21].

The structures of welded aluminium alloys, produced by laser and electron beam methods, are close enough [22]. The same relates to the joints produced with CO_2 and fiber laser radiation. Small weld width and volume

Table 3. Relationship of rate of butt welding modes of plates from alloy 01570 of 2 mm thickness using various type lasers [15]

Welding rate, m/min	Laser radiation power, kW	
	CO_2- laser	Fiber laser
2.0	1.6	1.1
3.0	2.6	1.4
4.0	4.0	1.9

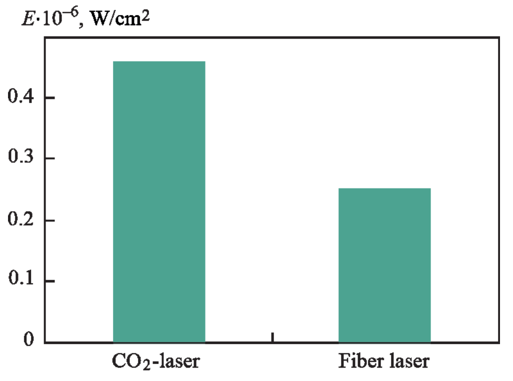

Figure 1. Dependence of threshold density of penetration power of alloy 01570 on type of laser radiation source [15]

of weld pool were observed in most of the cases of examined welded joints of aluminium alloys. Penetration with virtually parallel edges, weld shape coefficient $K < 1$ is achieved in welding of relatively thin materials (Figure 2, *a*) [23] or at certain increase of energy input (Figure 2, *b*) [24]. At that concavity and sagging of the weld are in allowable measures. Weld sagging (Figure 2, *c*) [25] can appear in case of welding with insufficient rate. In order to remove this defect it is relevant to use filler (and in case of hybrid welding — electrode) wire. In comparison with traditional consumable electrode welding (MIG, GMAW) the volume of molten metal in laser or electron beam welding is 2–3 time smaller (Figure 2, *d*) [26]. Close results are observed in comparison of highly-concentrated methods of welding with non-consumable electrode welding (TIG) [15, 20].

However, it is not always possible to get the certain weld shape by means of correction of welding mode. Thus, in welding of such high-strength alloys as 7075 to minimize such typical defects as pores and cracks it is relevant to reduce heat input (Figure 3) [27]. Concurrent local heating with simultaneous introduction of filler material, i.e. hybrid laser-arc process (Figure 4) [28], can be used in order to remove the defects mentioned above. Dosing of electric arc energy in hybrid process provides 30–60 % decrease of a volume of molten metal [29]. Thus, high-strength alloys (Figure 5) [30] are also used in welding of automobile structures (so called TWB — tailored welded blanks). Heat treatment is used after welding (annealing at temperatures about 450 °C) to get the possibility of their mechanical deformation (stamping).

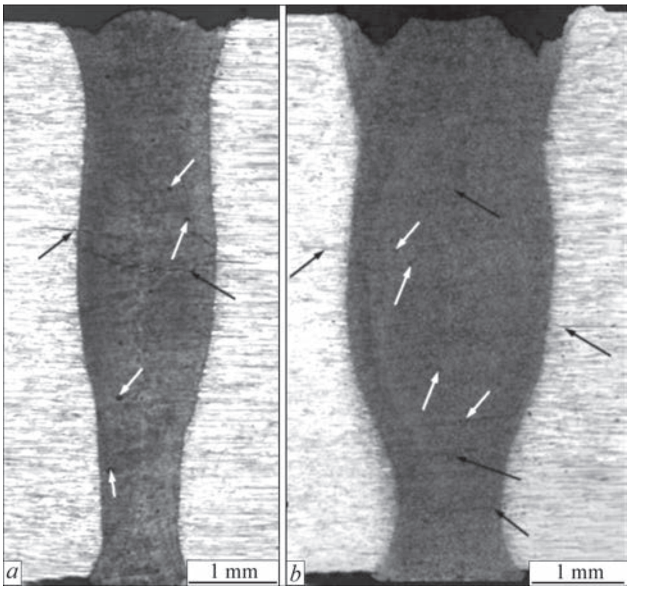

Figure 3. Microstructures of cross-sections of 7075 alloy joints (thickness 6.0 mm) produced by laser welding at different values of heat input [27]: *a* — 90; *b* — 180 kJ/m; black arrows indicate microcracks, white ones — microporosity

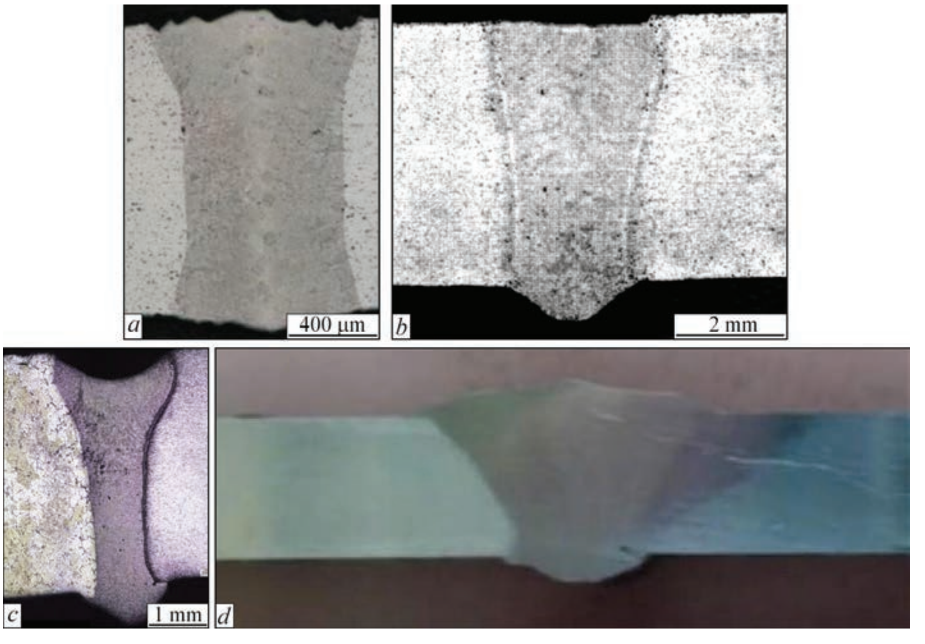

Figure 2. Results of welding of aluminium alloys using different methods: *a* — laser (alloy 6013, thickness 1.25 mm) [23]; *b* — electron beam (alloy 6061, thickness 5.0 mm) [24]; *c* — electron beam (alloys 2219 and 5083, thickness 5.0 mm) [25]; *d* — consumable electrode (alloy 6013, thickness 5.0 mm) [26]

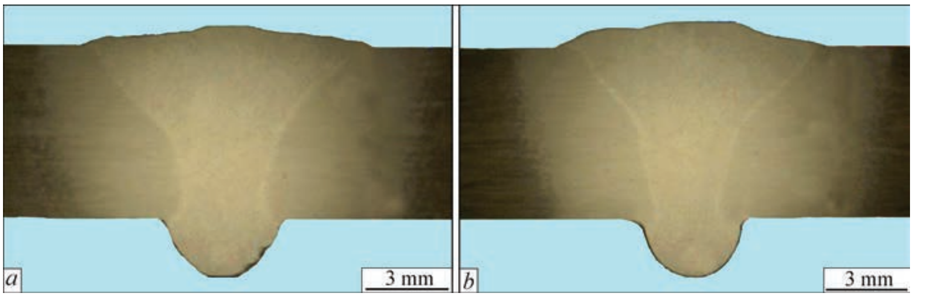

Figure 4. Microstructures of cross-sections of joints [28] produced by hybrid laser-arc welding of alloy 6082 (thickness 6.0 mm) using pulsed-arc consumable electrode welding (*a*) and CMT (cold metal transfer) process (*b*)

Laser welding with filler wire [31] or hydrid laser-arc welding [32] are relevant to use in order to remove weld concavity and achievement of stable formation of upper reinforcement bead. This allows reducing the requirement to butt joint assembly and obtaining the quality welded joints at gaps between the blank edges in 0.1–1.0 mm range. Diameter and rate of wire feed are selected based on thickness of material being welded and welding rate. Usually diameter of wire in laser welding makes 0.6–1.2 and in hybrid 0.8–1.6 mm. The optimum wire feed angle lies in 15–30° range from the joint area. The wire can be fed in front of the source of laser radiation or behind it during welding that can influence the efficiency and stability of the process.

One of the typical defects of welding of light alloys using highly-concentrated energy sources is a tendency to pore formation due to instability of penetration (pulsation due to keyhole effect) [20] as well as under effect of hydrogen, which is well solved in aluminium and beryllium at melting temperature [33, 34]. Increased susceptibility to porosity is typical for welding of aluminium–magnesium alloys, since magnesium rises hydrogen solubility in aluminium [35]. Treatment of surface before welding is used for porosity reduction for the purpose of removal of moisture absorbed by metal surface and oxide film, which contains hydrated oxides. The most effective for this is application of mechanical or chemical (etching) removal of the oxide film on 25–30 mm width from blank edges along the whole length of the joint [36].

Another typical defect of welding of light alloys using highly-concentrated energy sources is a susceptibility to hot cracking. The cracks can even be formed when using pulsed welding processes, which in comparison with continuous processes allow decreasing energy input in the material being welded. The most effective method for removal of this defect is weld alloying by means of introduction of filler material of corresponding composition. Thus, pulsed laser welding of heat treated aluminium alloy Al–4.7Mg–0.32Mn–0.21Sc–0.1Zr without filler metal and with filler metal of Al–5Mg alloy provoked formation of duplex (columnar and fine-grain) cast structures and gas porosity in form of defects in weld zone [37].

Application for welding of Al–5Ti–1B type filler metal provided formation of the fine-grain structure with an average grain size 4 ± 0.2 μm without weld defects. The average concentration of alloying elements in the weld made 2.8Mg0.2Mn0.1Zr0, 15Sc2.1Ti. Tensile strength of the weld made 260 MPa that corresponded to the values typical for the base metal in cast state. After annealing at 370 °C during 6 h this index rises by 60 MPa that made 85 % of base metal strength in as-rolled condition.

In addition to defects mentioned above, it is necessary to note the toxicity of welding aerosols being emitted [38]. Since beryllium content in the air should not exceed 0.001–0.003 mg/m^3, therefore it welding is usually carried out in closed chambers with controlled atmosphere that is provided by suction and filtering of formed harmful chemical compounds.

Investigations of weldability of beryllium and its alloys show that cast alloys on its base can be successfully welded using TIG, electron beam and laser methods [39]. Nevertheless, today for manufacture of critical structures of beryllium alloys the advantage is given to vacuum technologies such as electron beam welding and vacuum brazing [40].

The main obstacles for welding of beryllium are hot cracking, formation of cracks due to weld defects and low ductility [40]. Hot cracking can be reduced by means of control of chemical composition of beryllium being welded. Work [39] proposes to control Fe:Al relationship in such a way as it reaches less than 2.4 at his con-

Figure 5. Appearance of welded joints of alloys 5251 with 6082 [30] (thickness 1.5 mm) in the TWB (tailored welded blanks) products produced by electron beam (*a*) and laser (*b*) methods

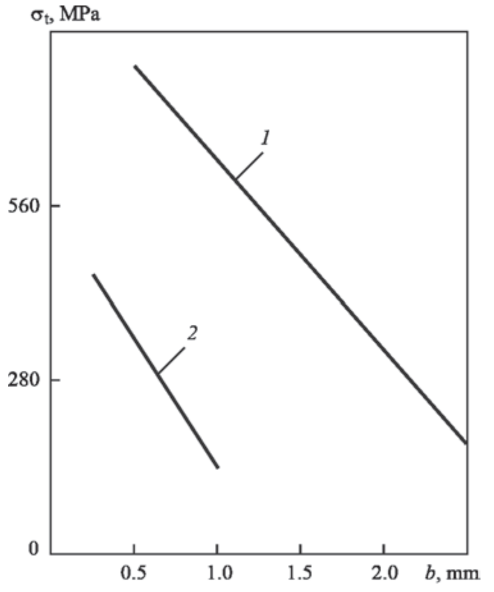

Figure 6. Dependence of ultimate strength σ_t of beryllium and its welds on grain size b [41]: *1* — base metal; *2* — weld metal

tent of iron and aluminium shall be minimum. Cracking related with the presence of defects and limited metal ductility can be reduced by decrease of BeO oxide and grain size of initial material. In addition, weldability of beryllium can also be improved due to decrease of welding rate, moderate heat input, minimizing fixing load of parts being welded as well as using corresponding pre- or concurrent heating. In some cases crack formation in the welds can be successfully removed by means of introduction of aluminium alloy filler into the weld pool. In this case it is necessary to take into account that usage of filler metal can reduce the operating temperature and yield limit of the welded joint.

Technological investigations of the peculiarities of the processes of beryllium welding using highly-concentrated energy sources showed its susceptibility to hot crack formation. The most effective way of their removal is decrease of temperature of local overheating of welded sample that is reached by reduction of the welding heat input, for example, as a result of increase of radiation power density through focusing using short-focus optics with simultaneous rise of welding process rate. Beryllium welding also leads to such defects as splashing of metal and irregularity of weld formation. They can be removed at proper selection of the welding modes, in particular the welding rate.

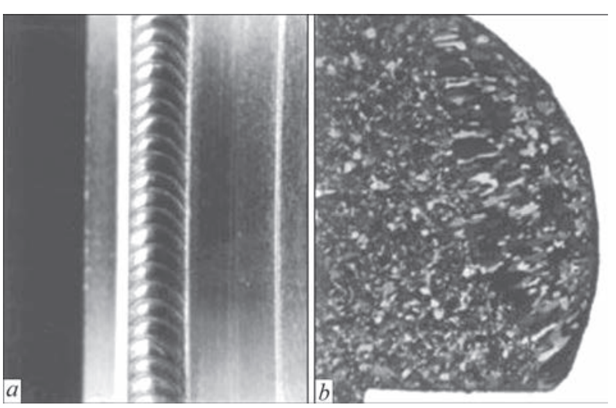

Figure 7. Laser welding of commercial structural beryllium [42]: *a* — appearance of weld of 25.4 mm diameter (ripple is formed by pulsed welding with points overlap); *b* — structure of cross-section of fusion zone, ×100

Application of special alloyed filler materials with aluminium in welding of beryllium and its alloy allows rising the joint strength from 0.5–0.6 to 0.7–0.8 of the base metal strength at simultaneous rise of ductility. Introduction into the weld of additional alloying elements permits rising strength with the help of post weld heat treatment, however themselves the alloys of Al–Be–Mg system are not heat treated. Such heat treatment provides production of full-strength welds compared to base metal [41].

Strength of the welds in welding of beryllium alloys significantly depends on size of crystallites of the weld metal (Figure 6). Refinement of weld structure is one of the way of production of the welded joints that on strength approach to the base metal: at 3–4 times (from 1.0 to 0.25 mm) decrease of the crystallite size the weld metal yield strength rises 3 times (from 137 to 412 MPa) [41].

In manufacture of the special beryllium parts for space satellites, for example, cylinder bodies of the power elements working at more than 600 °C temperature it is not permitted that foreign chemical elements come into the welded joints, therefore it is not allowed to use welding filler materials or replace welding by brazing [42]. Pulsed laser welding was used in this case. For welding of the body of energy source element its cylindrical part with a lid of 25.4 mm diameter being welded with girth weld was placed in a air-tight chamber with inert gas under required pressure and Nd:YAG-laser beam was passed through a transparent glass of this chamber. Cracking was eliminated using the pulsed radiation mode for welding (Figure 7).

An issue of laser welding of beryllium and its alloys in a controlled atmosphere as well as laser and electron beam welding in vacuum was studied in different works [43–45]. For example, work [45] describes the electron beam welding of beryllium alloys: A — 99.58 % Be + admixtures; B — 99.63 % Be + admixtures; C — 99.87 % Be + admixtures. The susceptibility of welded joints to formation of hot cracks across the weld was noted. At that, the direction of dendrite growth in solidification of weld pool metal resulted in weakening of longitudinal axial area of the weld (Figure 8).

The investigations of the values of residual stresses in Be–AlSi welded parts showed that welds strength to a significant extent depend on geometry of the structure, penetration depth and presence of defects, but much less on a level of residual stresses [46]. For analysis of the stressed state of cylinder shells from beryllium in work [47] there was carried out a modeling

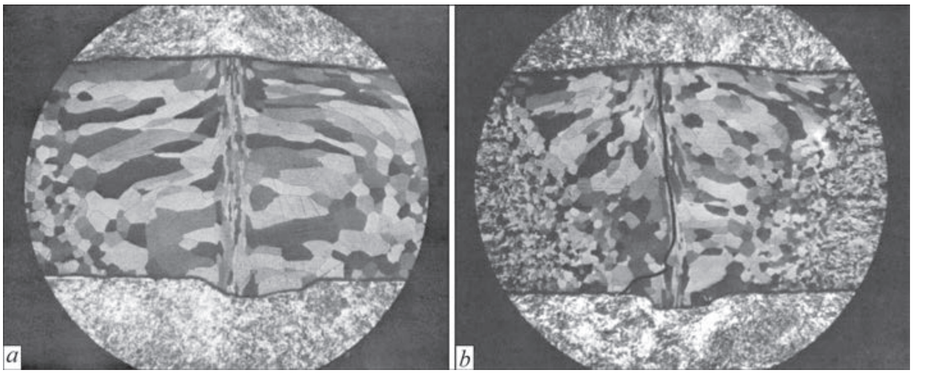

Figure 8. Microstructures (25) of welded joint produced by electron beam welding of beryllium alloys [45]: *a* — alloy C (δ = 1.5 mm), welded with preheating 400 °C, U = 100 kV; I = 7 mA; v = 8.5 mm/s; *b* — typical failure of welded joint of alloy A (δ = 2.5 mm) after tensile test

of temperature distribution in the process of their laser welding. Effect of laser power, radius of focusing spot and its displacement on temperature distribution in cylinder shells from beryllium was determined using a numerical modeling and multi-factor regression analysis.

The experiments carried in work [48] determined that the beryllium welded joints produced without filler material are characterized with very low ductility with strength about 50 % of base metal strength. Strength of the beryllium welded joints produced with aluminium filler materials made 70 % of base metal. Produced joints are characterized with high ductility.

THE MAIN GENERAL PECULIARITIES OF WELDING OF LIGHT ALLOYS USING HIGHLY-CONCENTRATED ENERGY SOURCES

The values of microhardness in the weld and heat-affected zone (HAZ) in laser and electron beam welding of light alloys are dramatically by 20–25 % higher than in TIG. A weakening zone in virtually absent in laser and electron beam welding whereas in TIG or MIG welding it spreads at a distance up to 1.0–1.2 mm and more from a fusion zone. Decrease of microhardness of HAZ metal relatively to the base metal makes about 13–14 %. Hardness of the areas of a near-weld zone in welding of hardened material decreases in relation with the base metal. An area of weakening by distance in laser and electron beam welding is 3–4 times less than in arc one.

The main disadvantages of welding of light alloys using highly-concentrated energy sources are the susceptibility to formation of inner pore and hot cracks. The most effective way for pores elimination are removal of oxide film before welding and quality protection of weld pool from atmospheric air. It is reasonable to decrease welding heat input and weld width, use filler materials for cracking elimination. One more variant of crack elimination can be pre- or concurrent heating of the parts being welded. From this point of view hybrid laser-arc and laser-plasma processes [49] are of high interest.

Application of the optimum modes of welding of light alloys using highly-concentrated energy sources, in particular in a range of rates more than 1.5–2.5 m/min, allows significantly reducing part deformation [50]. The investigations showed that the values of transverse shrinkage of the joints made by laser welding is 5–6 times less than in TIG welding [31, 51].

Unsatisfactory technological capacity to welding of 7xxx series alloys is caused by their high susceptibility to crack formation, high heat expansion coefficient and low temperature of evaporation of alloying elements such as zinc and magnesium that promotes appearance of cracks and porosity in welds. Work [25] demonstrates that the welds made by laser welding have higher tensile strength than in arc TIG welding. Work [35] shows that electron beam welding method is also reasonable for application with 7xxx series alloys. It was determined that hardness of a fusion zone is not improved after aging treatment and properties of HAZ are deteriorated independent on the welding method that indicates limitation of the possibility of increase of joint strength when using any welding process.

THE MAIN RESULTS OF ANALYSIS OF WELDING OF ALUMINIUM AND BERYLLIUM-BASED ALLOYS

It is advisable to perform welding of beryllium and high-strength aluminium alloys in vacuum (electron beam) or in a chamber with controlled atmosphere (for example, with agron under 100–101 Pa pressure) using fiber laser radiation. For welding of the part with small (δ = 1–3 mm) wall thickness the process rate shall be taken from 120 m/h and more (fore example, 150–200 m/h). At that radiation power lies in up to 1.0 kW limits. The expected peculiarities of weld structure formation are growth of grains and dendrites to the sides as for vertical axis of weld cross-section. This results in joint strength decrease. One more peculiarity of beryllium welding is high susceptibility to crack formation. In order to eliminate a danger of crack formation it is reasonable to reduce welding heat input and use pre- or concurrent heating (for example up to 150–200 °C).

The strength limit of light alloy joints made by welding using highly-concentrated energy sources depends on composition and can make 0.8–0.9 of base metal strength for aluminium alloys with satisfactory technological capacity to welding as well as about 0.5–0.7 for difficult-to-weld beryllium alloys. Failure of the joints welded without filler takes place mainly on a weld and ones welded with filler on a transition zone. The mechanical properties of welded joins are affected by weld composition which is changed due to evaporation of the alloying elements from a weld pool, particularly, such as magnesium, lithium, zinc etc. Decrease of content of these elements in the weld after welding can reach to 1.0–1.5 %.

In a series of cases after welding it is reasonable to carry out additional treatment of the produced joints in order to increase their mechanical properties. It can be heat treatment (annealing type), mechanical (for example, ultrasonic peening of welds) or any other.

One of the innovative methods of increase of welded joint quality is laser shock peening (LSP) [54], which was used for treatment of parts of aluminium alloy 7075 preliminary welded by laser radiation. The produced samples were subjected to corrosion strength examination under effect of mechanical tensile stresses using electron scanning microscopy (SEM) and slow strain rate testing (SSRT). The results showed that LSP treatment allows significantly rising corrosion resistance of the joints. Mechanical SSRT tests showed that the samples with LSP treatment have increased failure time and static toughness in comparison with untreated samples by 11, 20 and 100 % relatively to time and intensity of treatment. LSP also effects the change of nature and location of a fracture — type of crack propagation changes from inter to intracrystalline one. Such improvement of the joint properties is related, first of all, with microstructure refinement and decrease of the level of residual stresses.

CONCLUSIONS

1. Welding using highly-concentrated heat sources of wide range of light alloys can provoke such typical defects as hot cracks, inner pores, weakening of near-weld zone, weld sagging, undercuts and irregular nature of formation of reinforcement bead. To minimize the tendency to formation of indicated defects and production of quality joints it is relevant thoroughly select the welding mode parameters, remove oxide film from the blank surface before welding, provide reliable protection of the weld pool from effect of air, in separate cases use filler materials and pre- or concurrent heating. One of the advanced methods of elimination of indicated defects is application of hybrid laser-arc and laser-plasma welding methods.

2. The welds made by electron beam and laser (CO_2 and fiber laser) welding methods are quite similar by appearance as well as microstructure state and main geometry characteristics. Parameters of weld strength and heat input necessary for full metal penetration are somewhat different for various welding methods. Usually the heat input is approximately by 30 % lower for fiber laser than in CO_2-laser application.

3. Volume of molten metal in electron beam and laser methods is significantly smaller than in arc welding. In comparison with TIG and MIG welding there are significant decrease of weld width, 3–4 times drop of area of HAZ weakening and 5–6 times of level of residual deformations of the parts, whereas microhardness of the weld and HAZ rises by 20–25 %. The alloyed filler materials based on aluminium are good to be used for elimination of concavity of weld, increase of allowable assembly gap, increase of mechanical properties and decrease of metal susceptibility to crack formation.

4. Electron beam and laser welding of aluminium alloys provide welded joint strength at a level close to 80–90 % of base metal strength. In case of welding of beryllium alloys without filler material the joint strength is close to 50 % of base metal and at use of filler material based on aluminium it makes about 70 %.

5. The main peculiarity of gas-shielded laser welding of light alloys is the presence of a threshold values of penetration energy that is caused by intensive (over 90–95 %) reflection of laser radiation from the surface of welded blank as well as high values of alloy thermal conductivity. Energy input from 10^6 W/cm^2 is required in order to overcome the penetration threshold. Welding of the blank edges of up to 3.0 mm thickness shall be carried out using fiber laser radiation in argon shieldinged atmosphere with a rate over 120 m/h at radiation energy to 800–1000 W.

6. In beryllium welding the nature of growth of dendrites in solidification of weld pool results in decrease of weld strength, initiation of axial as well as transverse hot cracks is possible. The most dangerous zones for crack initiation are the crater being solidified as well as weld defects. Susceptibility of welds to crack formation can be reduced by means of application of preheating, decrease of welding heat input, usage of filler materials of specific composition, smooth reduction of power of highly-concentrated heat source at the end of welding process, removal of BeO oxide film before welding, minimizing the grain size of the initial material.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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