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MAIN PROBLEMS IN LASER WELDING OF THIN-WALLED STRUCTURES FROM ALUMINUM AND BERYLLIUM ALLOYS (REVIEW)

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ABSTRACT

The paper shows the results of analysis of current state of welding of thin-walled structures made of aluminum and beryllium alloys (so-called light alloys). Main problems and issues that may arise during laser welding of thin-walled structures from aluminum and beryllium alloys are determined. It is shown that according to the criteria of localization of heat deposition, minimization of the amount of residual deviation from the pre-defined shape and technological possibility of process implementation, a laser heat source may be widely applicable due to its possibility to form welded structures for aerospace purposes with a minimum level of residual stresses and deformations. Possible ways of eliminating problems that arise during laser welding of thin-walled aerospace structures from aluminum and beryllium alloys are proposed.

Keywords: Aluminum, Beryllium, Alloys, Welding, Laser, Mechanical Characteristics, Defects, Residual Deformations.

Light metals such as aluminum and beryllium, as well as their alloys, are widely used in the manufacture of modern mechanisms, in particular, in aircraft and rocket engineering. Their wide application is possible due to unique combination of properties: low density with high values of specific strength, corrosion resistance and thermal conductivity. The growing variety of structures made of these materials makes it necessary to create different methods of welding these materials. However, high thermal conductivity complicates the development of new welding techniques for these alloys. One of the most radical ways to reduce the effect of thermal conductivity on the residual stress-strain state of welded structures is to apply highly concentrated heat sources, in particular laser radiation. Welding processes that involve laser radiation allow to achieve high indicators of performance and quality of the obtained joints, are relatively stable and have good repeatability of results.

This paper aims to analyze literature and scientific publications on the topic of welding of thin-walled structures from aluminum and beryllium alloys in order to determine the main problems that arise during the process, as well as to determine possible ways to eliminate these problems.

Aluminum-based alloys are widely used in modern industry for the manufacture of lightweight structures with high strength and corrosion resistance.

Such structures may include products from such fields as instrument construction, chemical and food industries, electric power and electronic technologies, transport, etc. [1]. Metals containing beryllium are used much less frequently. Despite this, the production of such products is relevant for solving a number of problems in nuclear power industry, aerospace industry, etc. [2]. When manufacturing structures from light alloys (aluminum and beryllium), it is often necessary to obtain high-quality non-separable joints [3]. Various welding methods are used for these purposes [4].

In some cases, there is a need to weld heterogeneous joints from high-strength thin-walled aluminum alloys, for example, of 6xxx and 7xxx series [5]. Modeling of thin-walled structures from 6060 and 7003 alloys using the models, which are based on large shells prove the possibility of applying MIG welding. Plasma-arc welding technology is proposed for joinings of the technological rollers, necessary for fastening flanges in thin-walled large-sized cylindrical and spherical structures made of aluminum alloys [6]. Billets from aluminum alloys, in particular, thin-walled curved parts from Al-Li system alloys (for example, alloy 2195), are successfully welded by friction with stirring [7]. In [8], application of automated welding technology by Cold Metal Transfer for butt joints of thin-walled structures made of aluminum alloy AMg6 is substantiated. In some cases, ultrasonic spot welding is used to connect thin-walled parts, including made of aluminum and titanium [9].

In recent decades, laser welding has been used for welding critical thin-walled structures. Thus, the work [10] describes the use of laser welding for the manufacture of stringer fuselage sub-panels of aircraft casing. In [11], the possibility of replacing the traditional methods of riveting reinforced aircraft panels made of aluminum alloy by the laser welding method is proved. In [12], the resistance to compressive loads of a two-sided panel of an aircraft fuselage made of Al-Li alloy, welded by a laser, was considered. In a number of cases, laser welding is successfully used for welding precision thin-walled elements of devices and sensors [13]. Laser-MIG welding is used to manufacture a welded structure of a high-speed train body with a complex internal shape from thin-walled aluminum alloy profiles (thickness 2–4 mm) [14]. This process may minimize the formation of pores in the seams due to the action of an additional heat source (Fig. 1, a) and allows obtaining a joint with acceptable level of strength (Fig. 1, b).

a) b)

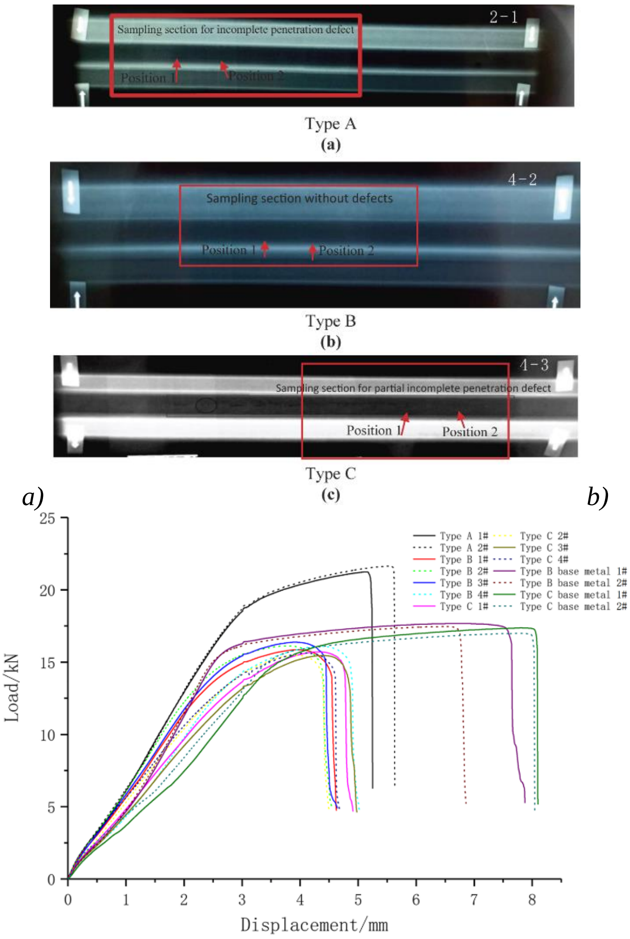


Fig. 1. Results of laser-MIG welding of 5754-H32 alloy [14]: a) – minimization of pore formation in seams; b) – results of static stretching of welded samples.

Despite a number of advantages associated with high thermal locality of laser welding, this process has certain disadvantages that make its industrial application more complicated. Thus, during laser welding of aluminum alloys, a characteristic defect is the formation of cracks, in particular, the appearance of hot cracks [15]. A feature associated with laser welding of thin-walled aluminum structures is the formation of pores due to surface tension [16]. The dynamics of welding bath during laser welding of aluminum alloys is influenced by their alloying elements (Fig. 2) [17]. At the same time, the increase in number of these elements and the transition to welding high-strength alloys are associated with an increase in the tendency to the formation of internal pores in the seams (Fig. 3). The features and results of the welding process are also affected by the type of laser, or rather the wavelength of radiation [18]. Another important aspect of the results of laser welding process is the strength of obtained thin-walled structures [19].

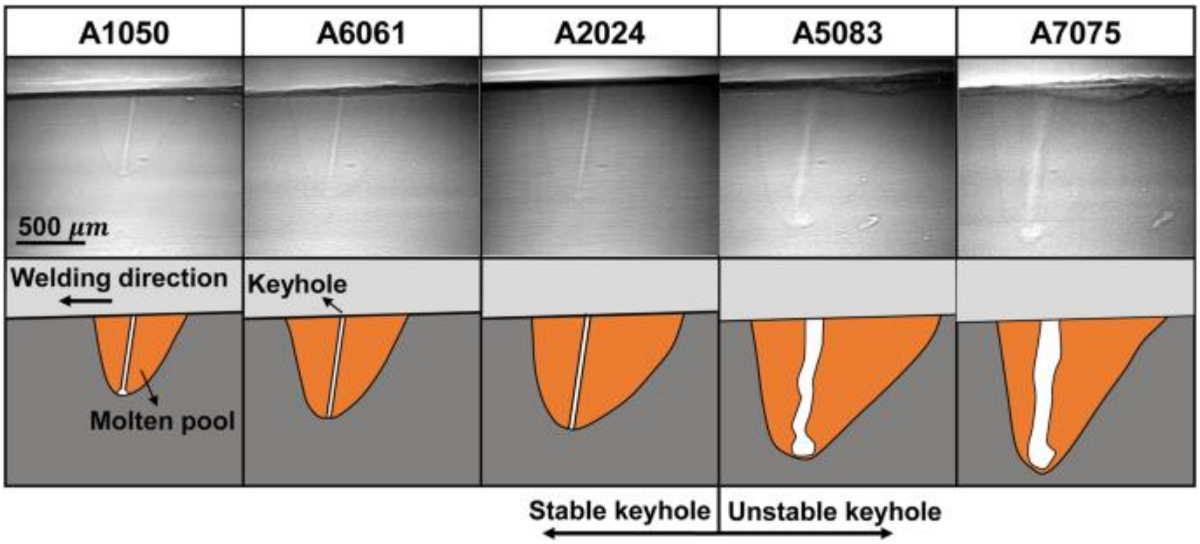


Fig. 2. A typical longitudinal view of a pool of molten aluminum alloys with different levels of alloying at a stable stage (photographed by an X-ray imaging system) [17].

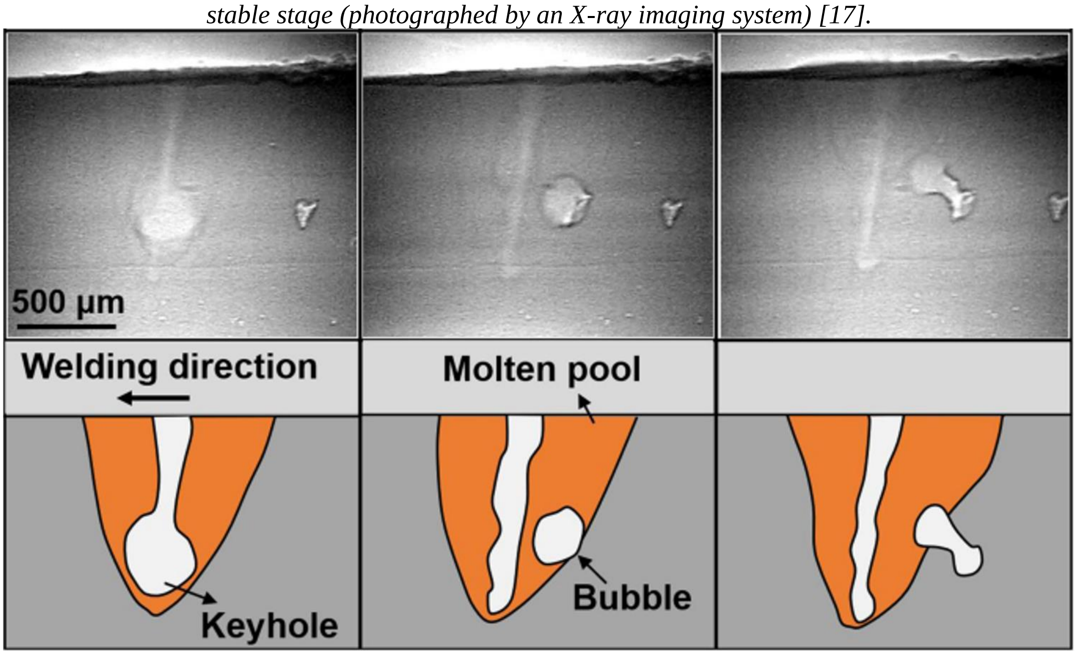


Fig. 3. Typical longitudinal view of the melt bath and the process of formation of an internal pore during laser welding of the A7075 alloy.

Traditionally, significant disadvantages of welded thin-walled structures made of aluminum alloys are residual deformation and low fatigue strength [20]. In order to take into account the influence of welding defects, it is necessary to apply software modeling of the temperature field and determine the structure of the joints of thin sheets with further prediction of welding deformations and residual stresses. In the case of laser welding, it is necessary to take into account the possibility of these shortcomings. However, compared to other welding technologies, those based on the application of laser radiation are best suited for solving the problem of welding thin-walled structures. In [21], it is shown that in the case of manufacturing thin-walled non-separable structures, it is advisable to use advanced laser or hybrid laser-arc welding methods capable of localizing the thermal heating of the weld zone.

The use of high-strength aluminum and beryllium alloys makes it possible to create lightweight structures with increased mechanical properties, which makes their use in modern industry relevant. High-strength beryllium alloys that are quite widely used include, first of all, the three-component "Local" system of Al-Be-Mg, grades of Lx-59-3 (59%Be, 3%Mg), Lx-40-3 (40% Be, 3%Mg). Among high-strength aluminum alloys, the alloys of the Al-Zn-Mg-Cu system (7xxx series), which have the highest mechanical properties, are of greatest interest. However, welding of such alloys is difficult due to their tendency to form hot cracks and pores. Therefore, studies of structure formation during welding of thin-walled joints from these alloys using concentrated energy sources are relevant.

Both traditional (arc or plasma) and more modern (laser and hybrid laser-plasma) fusion welding methods can be used to join thin-sheet aluminum and beryllium alloys. When using arc welding methods, the width of the seam usually exceeds the depth, which is determined by the convective mechanism of metal melting. In [22], it was shown that the intensity of such heat exchange and flow of liquid metal in the welding bath is influenced by alloying elements that act as surface-active substances. In addition, the temperature of the surface has an influence, therefore, the welding parameters. In work [23] it was shown that during welding with a freely burning arc, the force of the surface tension gradient and the electromagnetic force prevail in the convective flow of metal in the weld pool. The same penetration can be obtained during laser and laser-plasma welding [24]. At the same time, the dominant force factor determining the hydrodynamics of the melt is the Marangoni force. Convective energy transfer has the main influence on the formation of the molten zone in all the considered cases. Its shape and the amount of energy invested can lead to the formation of hot cracks (especially when welding high-strength and beryllium alloys) [25]. It is more effective to use laser and laser-plasma welding with such penetration, in which the width of the penetration is less than the depth. This type of penetration is called deep and is characterized by the formation of a steam-gas channel [26]. Peculiarities of the existence of the steam-gas channel are related to its pulsations, which can contribute to the formation of pores in the remelted metal [27]. The formation of cracks is associated with an increase in the crystallization rate of low-melting eutectics, the appearance of which is caused by an increase in the welding speed [28]. An increase in the critical rate of deformation of welds (in the example considered in Fig. 4 from -4%/s to -1%/s) helps to reduce the tendency to hot cracking (by 75%), primarily due to the optimization of laser welding modes. In addition to pores and cracks, defects such as the formation of undercuts on the surface of the seam in the fusion zone, uneven formation of reinforcement rollers, sagging seams, etc. may occur [29].

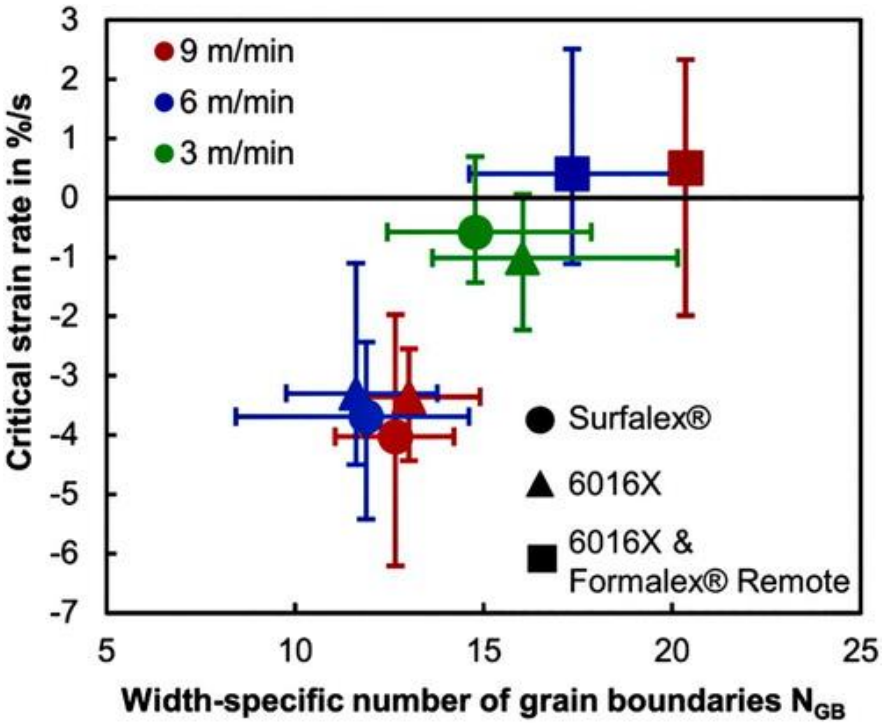


Fig. 4. Critical rates of deformation of welds of various aluminum alloys of the Al-Mg-Si system, welded at different speeds, depending on the specific number of NGB grain boundaries across the width of the seam [28].

The joints of high-strength aluminum alloys of 7xxx series and alloys with a high content of beryllium (such as "Localoys") are more prone to the formation of cracks and pores. In [25], it is showed that evaporation during laser welding leads to a change in the concentration of volatile elements, primarily magnesium and zinc. This changes the crystallization rate of the weld and thus the susceptibility to hot cracking. This effect is largely influenced by the welding speed. In [30], it is shown that alloys of the 7xxx series have poor weldability due to their high tendency to crack formation and coefficient of thermal expansion, as well as low evaporation temperature of Zn and Mg elements. This contributes to the formation of such welding defects as cracks and porosity (Fig. 5). Similar defects can be detected in the case of welding deformed alloys of other series with lower strength [31]. In addition, when welding alloyed aluminum alloys, the presence of oxide inclusions in the remelted metal is also possible. Recently, a number of approaches have been developed to minimize and eliminate these defects. Basically, such approaches are focused on welding with penetration with the formation of a through channel (keyhole) [31].

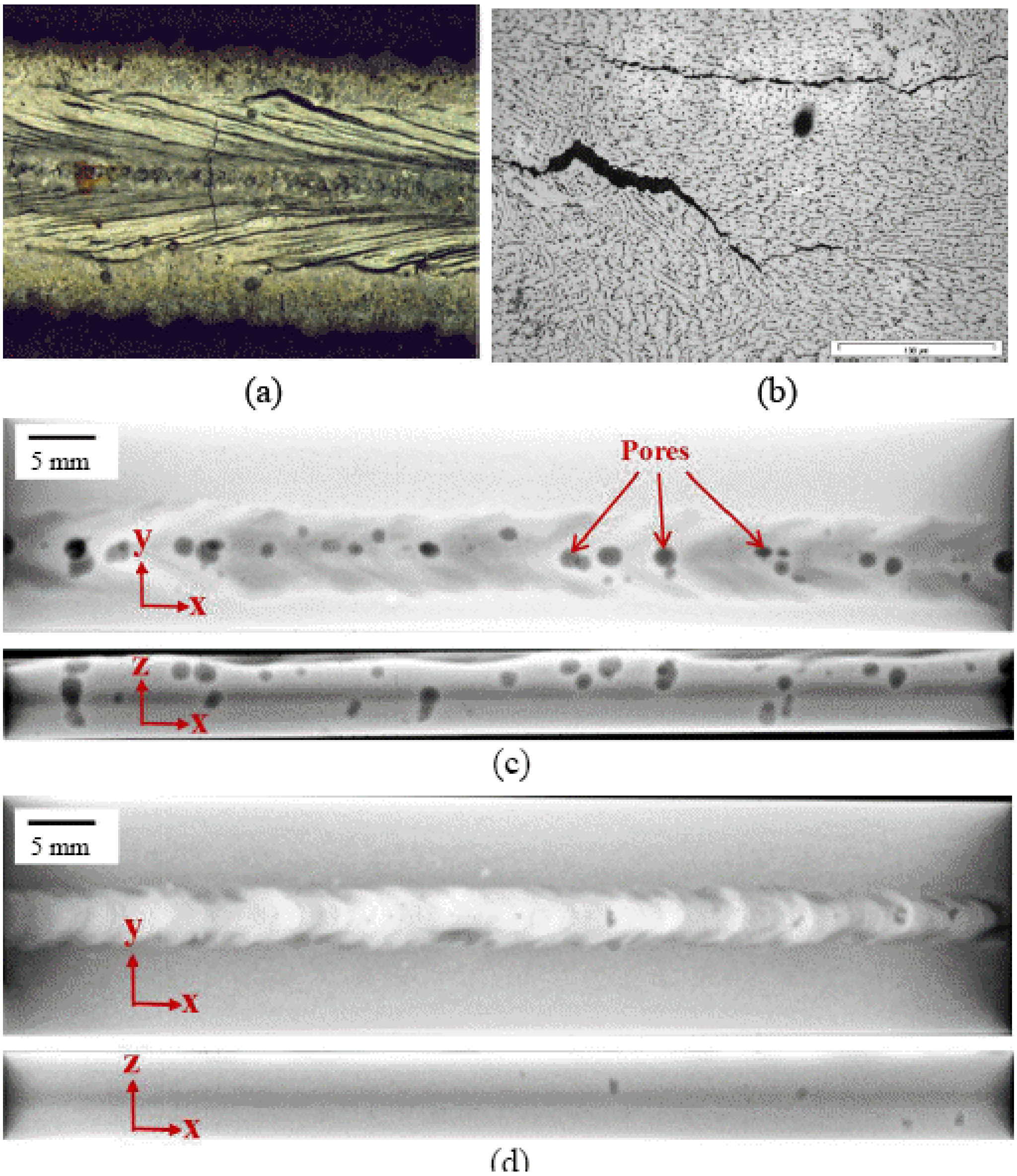


Fig. 5. Defects of welds: a) – transverse cracks on the upper roller of the Al7075 sample, welded by the laser-arc method; b) – a typical crack in the HAZ of the Al7075 sample welded by the laser method; c) – radiograph showing the degree of porosity in the Al7075-T651 sample welded by the laser-arc method; d) – radiograph of seams obtained by laser welding with cold wire 4043.

When choosing filler materials for welding light alloys, it is recommended to take into account a number of main factors [32]. These include good weldability or absence of cracking, tensile or shear strength of weld, ductility of weld, operating temperature range, corrosion resistance, and color match between the weld and the base alloy after anodization. Among aluminum alloys, alloys of 7xxx series have become the most popular today due to such a complex of their properties as high static and dynamic strength, heat resistance, high impact toughness, resistance to damage, low density, low sensitivity to hardening, etc. [33]. However, due to high mechanical properties, welding of these alloys is problematic.

One of the promising approaches to joining alloys of the 7xxx series is friction stir welding [34]. However, in this case, due to the release of heat during welding, the strength of the seams decreases and post-weld heat treatment is required (Table 1), which leads to undesirable coarsening of the grains in the joint [35]. The best results are achieved when friction stir welding is used to join alloys of the 7xxx series with alloys of other series that have better weldability. An example can be the combination of these alloys with alloys of the 2xxx series [36]. AA2139-T8/AA7020-T651 joints were friction stir welded with rotation and feed speeds in the range of 600-1000 rpm and 250-550 rpm, respectively. The yield strength of the joints was 77-79%, the tensile strength was 88-96% of the base material AA7020 (Fig. 6). However, in a number of cases, defects occur on the side of the 7xxx series alloy. Thus, during friction stir welding of 2017A/7075 aluminum alloys, plastic deformation increases the hardness of the 7075 alloy, which leads to a weakening of the seam zone [37].

Table 1.

Relative values of tensile strength (efficiency in %) in the transverse direction of heat-treated joints of aluminum alloys obtained by friction stir welding [34].

Material	Thickness (mm)	Efficiency (%)
AA 2014	8,0	75
AA2014-T651	6,0	68–70
AA 2017-T351	5,0	82
AA 2017A-T451	20,0	90,8
AA 2024-T3	3.0	88
AA 2024-T3	4.0	83
AA 2024-T3	4.0	89–90
AA 2024-T4	3.0	60
AA 2219-T6	6,0	71
AA 2219-T6 (УВ)	7,5	83,3
AA 2219-T87	–	65
AA 2519-T87	6,0	57–62
AA 2519-T87 (УВ)	6,0	65–76
AA 6013-T4	4.0	93
AA 6013-T6	4.0	74
AA 6061 (AB)	6,0	66
AA 6061(CT)	6,0	59
AA 6061 (CTA)	6,0	63
AA 6061(AГ)	6,0	77
AA6016-T4	1,0	~80
AA 6061-T6	5,0	74
AA 6056-T78	6,0	74,4
Aл 6082-T6	8,0	75–81
AA7020-O	12,0	100
AA7020-T6	4.4	84
AA7039-T6	5,0	85,6
AA7039-W	5,0	93,8
AA7039-O	5,0	98,2
AA7050-T7451	6.4	77–81
AA 7075-O	3.17	100,2–101,2
AA 7075-T6	3.17	67,8–79,8
AA 7075-T6	3.0	75
7050-T7451	6,35	70–75
AA7075-T651 (AW)	12,0	69,9
AA7075-T651 (AГ)	12,0	55,7
AA7075-T651 (CTA)	12,0	79
AA 7349-T6	10,0	81

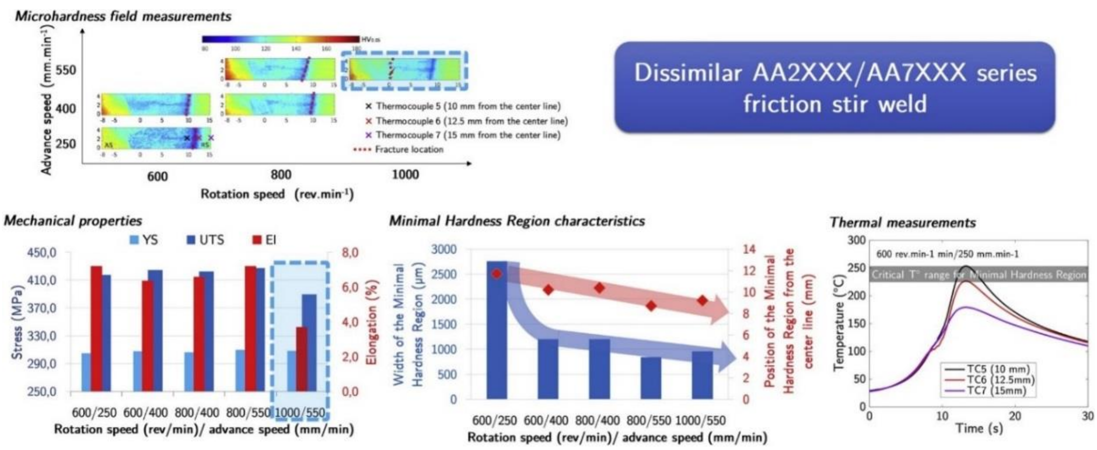


Fig. 6. Physico-mechanical characteristics of welded joints AA2XXX/AA7XXX obtained by friction with stirring [36].

Modern technologies make it possible to weld light alloys, which until now were considered difficult to weld [38]. Such technologies include not only friction stir welding, which is successfully used due to the absence of melting in the welding zone. A number of innovative processes have been developed, such as arc welding with low heat input, as well as fusion welding with high power density (laser and electron beam welding) [39]. An example can be laser butt welding of a package of high-strength aluminum alloy sheets with radiation scanning (Fig. 7) [40].

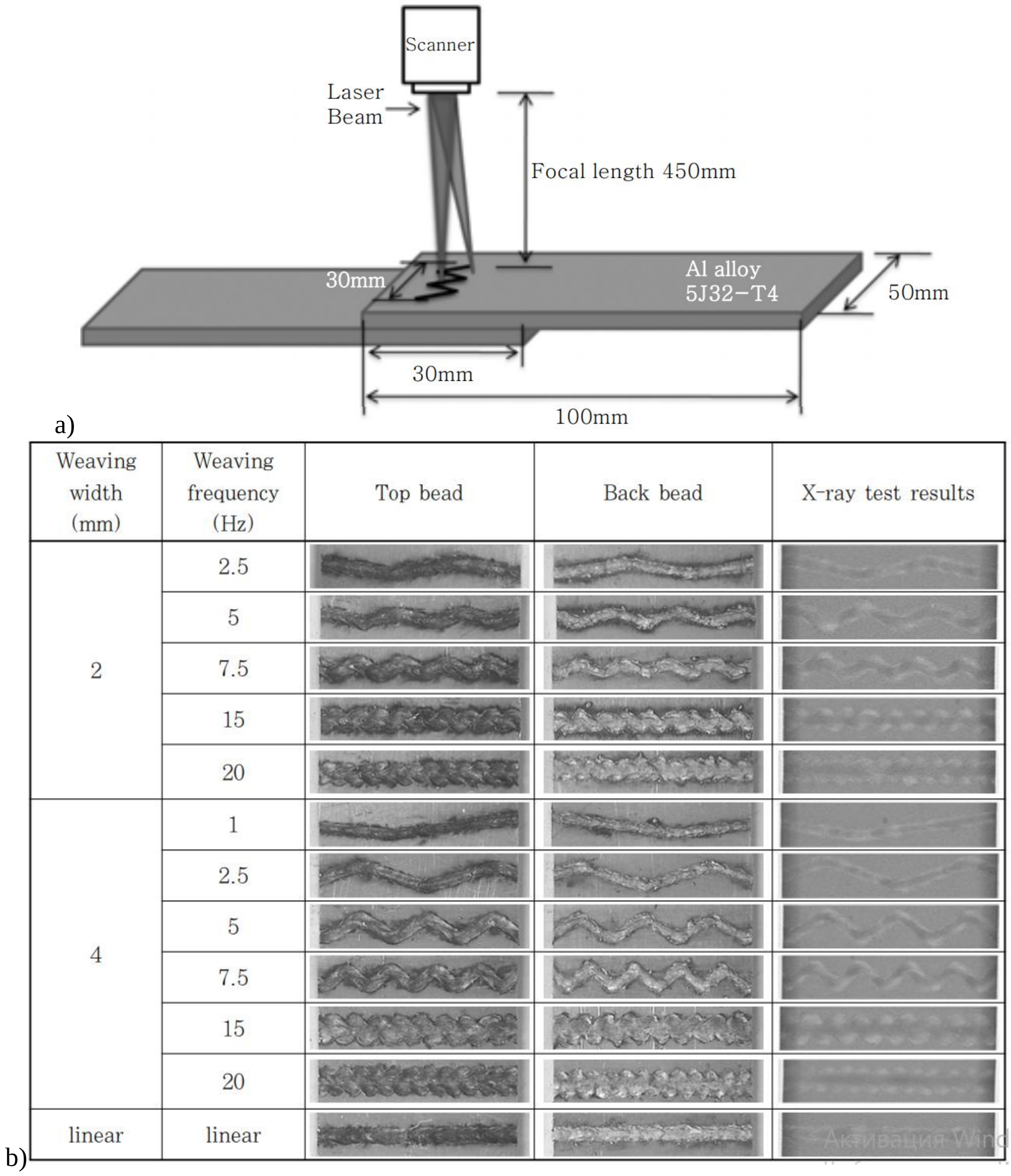


Fig. 7. Scheme of process (a) of laser butt welding with a slotted seam with radiation scanning and the appearance (b) of rollers and the results of their X-ray examination [40].

Innovative light alloy welding processes include the GAMW multi-layer and multi-pass welding technology, developed for joining aluminum alloys 5083, 6005A and 7N01 with a thickness of 10 mm, used in high-speed trains of the Chinese Railways [41]. The tensile strength of the obtained joints reached 323, 206 and 361 MPa for alloys 5083, 6005A and 7H01, respectively. Contact welding can be used for welding alloys of the AA5xxx and AA6xxx series, including when dissimilar joints are obtained [42].

Arc welding with a tungsten electrode in a protective gas environment (TIG or GTAW) is an important method of joining high-strength aluminum alloys, which are increasingly widely used in the aerospace, aviation, automotive industry, in the manufacture of rocket engines, for rockets, marine engine components, etc. [43]. However, this technology has been developed to a greater extent for less strong alloys, including the 6xxx series (for example, the AA6105 alloy) [44]. When dissimilar joints of 2024 T3 and 7075 T6 aluminum alloys are obtained by the TIG (GTAW) method, there is an increase in brittleness and a drop in tensile strength by 44% and 37% in base metals 7075 T6 and 2024 T3, respectively [45].

In [46], it is shown that one of the promising technologies for joining high-strength alloys 7025-T6 and AW-7020 is pulsed MIG welding. With constant heat supply in the process of such welding, the speed practically did not affect the hardness of the weld. However, the grain size increased with increasing filler wire feed rate, welding current, and welding speed. High driving energy led to a decrease in the stiffness of the weld. Preheating was detrimental to AW7020 welds, but artificial aging proved beneficial. Acceptable seams were obtained using pulsed MIG welding without first removing the Al2O3 layer. It was established that the Al2O3 oxide layer has a different composition in different aluminum alloys.

The main feature of the welding of beryllium and its alloys is the toxicity of the welding aerosols that are released during this process [47]. The content of beryllium in air should not exceed 0.001-0.003 mg/m3. Therefore, its welding is usually performed in closed chambers with a controlled atmosphere, which ensure their suction and filtration.

Studies of the weldability of beryllium and its alloys show that cast alloys based on it can be successfully welded by TIG, electron beam and laser methods [48]. However, today vacuum technologies such as electron beam welding and vacuum brazing are preferred for the manufacture of responsible structures from beryllium alloys [49].

The main issues for beryllium welding include hot cracking, formation of cracks due to weld defects and low plasticity [49]. Hot cracking can be reduced by controlling the chemical composition of the welded beryllium alloy so that the Fe:Al ratio reaches up to 2.4, while the amount of iron and aluminum is minimized [48]. Defect cracking and ductility-restricted cracking can be reduced by reducing the amount of BeO oxide and the grain size of the starting material. The weldability of beryllium can also be improved by reducing the welding speed, moderate heat input, minimizing the clamping forces of the parts to be welded, and using appropriate preheating. In some cases, cracking in the seams can be successfully eliminated by introducing an aluminum alloy filler metal into the weld pool. In the latter case, it should be taken into account that the use of filler metal can reduce the working temperature and strength limit of the welded joint.

The use of special alloyed additives with aluminum when welding beryllium and its alloys allows you to increase the strength of the joints from 0.5...0.6 to 0.7...0.8 of the strength of the base metal while simultaneously increasing plasticity. The introduction of additional alloying elements into the seam makes it possible to increase strength due to heat treatment, while alloys of the Al-Be-Mg system are not heat-strengthened. Such heat treatment ensures uniform strength of the seam with the base metal [50].

The strength of seams when welding beryllium alloys largely depends on the size of crystallites of the weld metal (Fig. 8). Grinding the seam structure is one of the ways to obtain welded joints that are close to the base metal in terms of strength: when the crystallites are reduced by 3-4 times (from 1.0 to 0.25 mm), the strength limit of the seam metal increases by approximately 3 times - from 137 to 412 MPa [50].

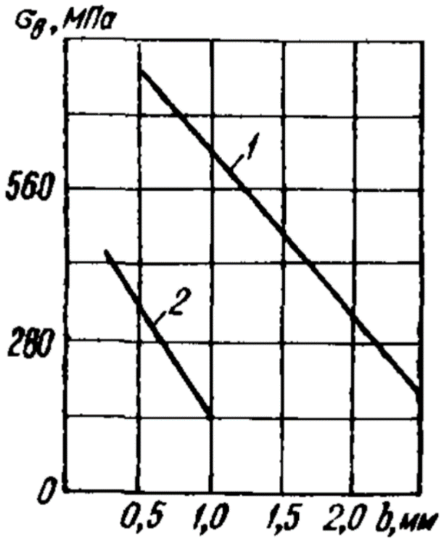


Fig. 8. Dependence of the strength limit σв [MPa] of beryllium and its welded joints on the grain size b [mm] [50]: 1 – base metal; 2 – seam metal.

In the case of welding without through penetration and keyhole formation, the thermal mode of laser welding changes (Fig. 9), which leads to a change in the structure of the metal being welded, as well as an increase in the risk of pores and cracks in the lower part of the seam [51]. However, sometimes there is a need to perform seams with non-through penetration. An example can be sealing seams, which are performed in closed trajectories (for example, circular) when welding flanges or manufacturing small parts. In such cases, sealing may be required as a final assembly operation. In the volume that is sealed, electronic elements can be installed, which makes it inadmissible to remove the root of the seam into it. At the same time, the choice of mode parameters is complicated by the fact that for the same linear energy (for example, 13 J/mm [52]), welding processes can take place both in the convective mode and in the keyhole formation mode.

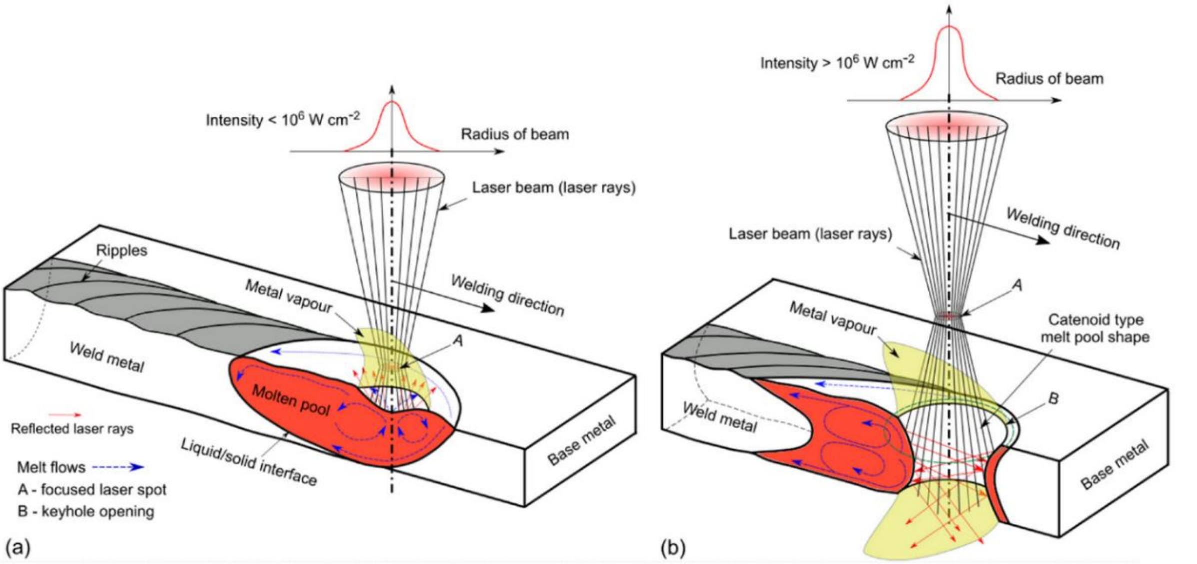


Fig. 9. Schematic illustrations of laser welding processes with an indication of melt flows [51]: a) – mode of heat conduction penetration (the beam is focused near the surface); b) – keyhole keyhole mode (defocused beam).

In case of multi-pass laser welding, there is also a need to form welds with non-through penetration. In [53], it was established that short thermal cycles during multi-pass laser welding lead to insufficient diffusion time of elements of the welded alloy, which leads to better preservation of the structures of the base metal. Additionally, the applied heating cycles during multi-pass laser welding contribute to the formation of interconnected microstructures that contribute to increasing the strength of the welded joint.

One of the defects characteristics of micro-plasma butt welding of thin-sheet aluminum alloys is the sagging of the seams [54]. To eliminate this defect, both laser and laser-plasma welding can be used [55]. Laser and hybrid welding is effective if it is necessary to obtain connections with non-through penetration, for example, butt joints (Fig. 10). However, from the point of view of economic and technological expediency, laser-microplasma welding has the advantage. In [54], it isestablished that the formation of undercuts and internal pores in the seams can be characteristic defects of this process. The causes of such defects are mainly related to the gas dynamics of the plasma jet, the pressure of the plasma arc and the design of the integrated plasmatron. In this connection, work was carried out on the study of the outflow of plasma-forming and protective gases from the corresponding nozzles of the integrated plasmatron, as well as the placement of electrodes in it. This made it possible to develop an improved design in which the paraxial single-electrode circuit [56] was replaced by a symmetrical two-electrode coaxial circuit [57]. The created principles were the basis for further development of a universal integrated plasmatron for hybrid welding and cutting processes [58].

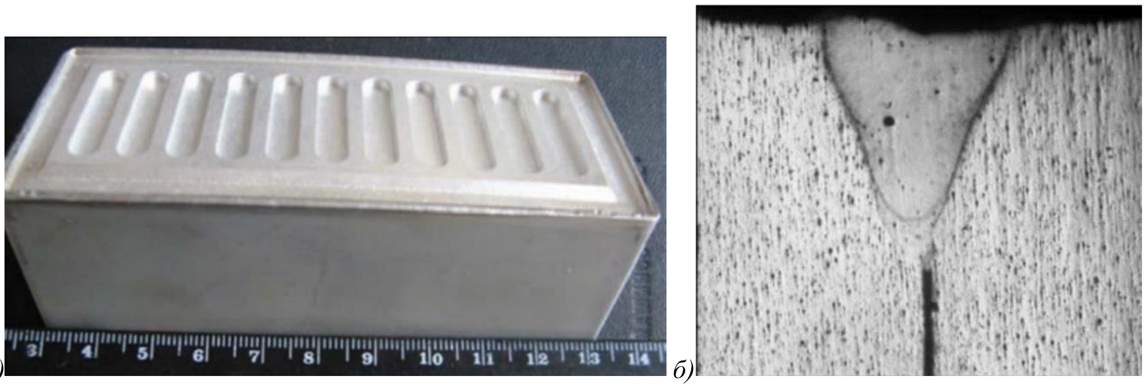
a)  *б)*

Fig. 10. Examples of application of laser and hybrid welding with non-through penetration: a) – external appearance of a fragment of the battery case made of aluminum alloy AMg6, 0.8 mm thick, connected by laser welding [55]; b) – macrostructure (×25) of the cross-section of the end joint of AMg6 alloy (δ=1.4 mm), made by hybrid laser-plasma welding at a speed of 168 m/h [54].

In the analyzed works, questions related to the peculiarities of the formation of seams without through penetration remain unresolved. First of all, this concerns the occurrence of characteristic defects and suggestions for ways to eliminate them. No information was found in the literature about the metallurgical features of the formation of joints of high-strength aluminum and beryllium alloys with seams of this type and about the choice of the optimal technology for obtaining a butt sealing seam with non-through penetration.

In general, it can be noted that in welding of thin-sheet light alloys by laser, arc and hybrid methods, may arise the following problems:

- obtaining a connection with the base metal of different strength, due to the difference in the sizes of the weld metal grains, the fusion zone of the weld with the base metal, the heat affected zone (HAZ) and the base metal;
- the formation of undercuts on the surface of the weld along the fusion zone, caused by the short existence of the welding bath in a liquid state and the absence of the possibility of normal spreading of the liquid metal until the moment of its crystallization;
- the appearance of pores in the weld metal, associated with a change in the solubility of hydrogen in the aluminum alloy at different temperatures;
- the appearance of hot cracks due to the presence of eutectic compounds in the weld metal and changes in the conditions of their solidification from the molten metal at different crystallization rates due to different welding driving energies.

In order to minimize the impact or completely eliminate the problems, which were mentioned above it is advisable to establish the regularities of the influence of the parameters of the laser welding process modes and the joint action of laser and plasma heating sources on the structure, the formation of characteristic defects and the peculiarities of the flow of thermomechanical processes in welded joints from aluminum and beryllium alloys, as well as to develop new techniques for obtaining thin-walled welded structures with a minimum level of residual stresses and deformations, as well as equipment for their implementation. The main ways to eliminate the main problems that arise during laser welding of thin-walled aerospace structures made of aluminum and beryllium alloys are the following:

- performing an analysis of the current state of welding of thin-walled structures from light alloys, justifying the choice of a heat source for welding thin-walled structures from light alloys, which allows forming welded structures for aerospace purposes with a minimum level of residual stresses and deformations;
- selection of necessary materials and equipment and research methods;
- development of calculation methods and implementation of forecasting of parameters of welding regimes of various types of light alloys using laser radiation, taking into account the requirements for penetration, performing its experimental verification for aluminum and beryllium alloys, establishing the peculiarities of the flow of physical and metallurgical processes during laser welding of these alloys in a chamber with controlled atmosphere;
- performing mathematical modeling of the temperature distribution in thin-walled products made of light alloys when they are heated by a laser heat source, including taking into account the requirements for the average temperature of specific products after local heating during the welding process;
- determining the influence of parameters of laser welding modes and conditions on the level of residual deformations and stresses by modeling thermal deformation processes during laser welding of thin-walled products made of light alloys;
- development of basic structural elements of equipment to create a research and industrial complex for welding aerospace products from light alloys;
- development of techniques and equipment for non-destructive testing and determination of the level of residual deformations and stresses of high-precision thin-walled welded products made of light alloys for aerospace purposes by the method of stereo-digital 3D image correlation.

On the basis of performed analysis of literary sources, the following conclusions are made:

1. Analysis of current state of welding of thin-walled structures from light alloys showed that according to the criteria of localization of heat input, minimization of the amount of residual deviation from the given shape and manufacturability of the process, a laser heat source is the most acceptable, which allows forming welded structures for aerospace purposes with a minimum level of residual stresses and deformations.

2. The main defects of seams in welding of aluminum alloys include hot cracks, internal pores, undercuts and sagging seams. One of the effective ways to eliminate cracks is to reduce the running energy, internal pores – to eliminate the ingress of the oxide film into the welding bath, sagging seams – the use of additive materials. To eliminate undercuts, it is advisable not only to select the thermal and high-speed modes of welding, but also to take into account the dynamics of gas flows and the pressure of the arc on the welding bath.

3. The growth of dendrites during crystallization of the weld pool in welding of light alloys leads to a decrease in the strength of the seam in the area of the vertical axis of the cross section. In addition, when welding light alloys, the appearance of both axial and transverse hot cracks is possible. The most dangerous areas of crack formation are the crystallization crater, as well as seam defects. Ways to eliminate cracking are: preheating, minimization of welding power, use of additive materials, gradual reduction of laser radiation power after welding, elimination of oxide film before welding, and, if possible, reduction of the grain size of the starting material.

4. One of the sufficiently effective and universal ways of eliminating defects that are typical for laser welding of aluminum alloys is to use the accompanying action of electric arc energy source, in particular, the additional plasma heating of the welding bath. This method allows to minimize formation of pores, improve formation of the upper roller, eliminate undercuts and partially replace laser energy with plasma.

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