https://doi.org/10.37434/tpwj2022.05.03

SELECTION OF PARAMETERS OF LASER WELDING OF THIN-WALLED ITEMS FROM LIGHT ALLOYS WITH NONTHROUGH THICKNESS PENETRATION

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ABSTRACT

Light metal alloys (in particular, beryllium and aluminium) are applied in different engineering fields, for instance for fabrication of rocket and aircraft elements. When designing such engineering elements, there is the need to produce welded joints with different types of welds. Laser welding with nonthrough thickness penetration welds can be used for item sealing, welding-on flanges and welding thin-walled structures of up to 2–3 mm thickness. Toxic fumes form in welding beryllium alloys. Such a peculiarity requires reducing the number of technological experiments, aimed at selection of mode parameters. An up-to-date approach to solving the problem of light alloy welding is performance of preliminary calculated determination of mode parameters with their further experimental verification. Technological verification can be performed on high-strength aluminium alloys close by their physico-mechanical characteristics to beryllium alloys. Therefore, this work is devoted to preliminary determination of mode parameters of laser welding by a sealing weld with nonthrough thickness penetration of thin-walled flanges of cylindrical parts and box-shaped items from light metals and alloys based on Be and Al, taking into account the temperature of postweld heating. A procedure of preliminary calculated determination of mode parameters of laser welding of parts from a beryllium-based alloy is proposed in the work, which is suitable for both through-thickness and nonthrough-thickness penetration. Nonthrough-thickness penetration can be applied for welding-on flanges by a sealing weld. Experimental verification on samples from alloys of Al–Zn–Mg–Cu system and comparison with published data on beryllium alloy welding showed that the error of the proposed procedure is in the range of up to 15–20 %.

KEYWORDS: laser welding, light alloys, penetration, mode parameters, error, pores, cracks

INTRODUCTION

Light metal alloys (beryllium, aluminium and magnesium) are applied in different engineering fields. In particular, they are used for manufacture of rocket and aircraft elements. When designing such engineering elements, it is necessary to produce welded joints. Welds of different types are used when making such joints. In particular, welds with nonthrough thickness penetration can be used for item sealing (for instance, welding flanges) and welding thin-walled structures up to 2–3 mm thick. In this case, it is necessary to apply highly efficient welding technologies, which allow achieving a guaranteed penetration depth in combination with minimizing residual welding deformations. This result is the easiest to achieve by applying welding with increased localization of thermal impact on the base metal. Laser welding is an example of one of the most acceptable welding processes [1].

A feature of welding structures, containing beryllium (actually, beryllium, beryllium-based alloys and aluminium-beryllium alloys), is toxicity of fumes, formed in the process. Such a feature requires reducing the number of preliminary technological experiments, aimed at selection of mode parameters. A similar approach is desirable also for selection of parameters of welding other light alloys (based on aluminium and magnesium). Therefore, a relevant approach to solving this problem is performance of preliminary calculation-based determination of mode parameters with further experimental verification. Preliminary technological verification can be performed on high-strength aluminium alloys close to beryllium ones by their physico-mechanical characteristics.

ANALYSIS OF PUBLISHED DATA AND PROBLEM DEFINITION

Studying the features of welding parts from high-strength beryllium and aluminium alloys, for instance, alloy of Be–AlSi system, showed that the weld strength largely depends on the structure geometry, penetration and presence of defects, and to a much smaller extent — on residual stresses [2]. Therefore, it is rational to base selection of laser welding parameters on certain geometry of penetration. One of the main defects of laser welding of the above-mentioned light alloys is pore formation that is largely related to the features of existence of the vapour-gas channel [3]. Therefore, it is necessary to take into account the behaviour of the vapour-gas channel, forming during laser radiation absorption by the base metal.

In work [4] the dynamics of weld pool behaviour at laser welding of aluminium alloys of different series is considered. Experiment results showed that at laser irradiation the metal evaporates with formation of a vapour-gas channel. This is followed by gradual melting of the metal, surrounding the vapour-gas channel, under the impact of heat evolving in it. The rate of increase of channel depth is directly proportional to overall content of elements with a low boiling temperature. At the stationary stage of the penetration process the channel depth and diameter are stabilized. In the longitudinal direction the melt pool area is inversely proportional to aluminium alloy heat conductivity. The rate of laser radiation absorption changes depending on the ratio of vapour-gas channel depth to its diameter and reaches the largest value of 58 %. In the case, if the surface tension and recoil pressure of the metal vapours are balanced, abrupt changes of the channel shape can be avoided.

In addition to vapour-gas channel behaviour, the metallurgical aspects also influence the weldability of high-strength light alloys. The main difficulties in welding these alloys are hot cracking, pore formation, cracking on defects (pores), lowering of ductility in the welds and HAZ. The following measures can be used to solve these problems [5]: control of Fe/Al ratio in the base metal to lower the hot cracking susceptibility, minimizing the content of oxides and initial grain size to limit crack formation on the defects and to increase the ductility, as well as selection of the process of welding and optimization of its parameters.

To reduce hot cracking of welded joints, it is rational to optimize such mode parameters as laser radiation power, welding speed, specific power and focal position [6]. This approach allows minimizing the welding heat input. Addition of filler metal of another chemical composition also promotes lowering of cracking sensitivity. This way it is possible to improve the joint ductility that promotes crack elimination [7]. In order to reduce porosity and improve the weld strength, it is necessary to avoid penetration of oxide film (Al_2O_3 and/or BeO) into the weld pool [8]. For this purpose, it is rational to remove this film from the surfaces being welded directly before welding.

Note that filler material application in welding beryllium alloys is not always possible. So, in manufacture of some specialized beryllium parts for space satellites (for instance, cylindrical cases of energy source elements, operating at temperatures higher than 600 °C) penetration of extraneous chemical elements into the welded joints is inadmissible that does not allow applying welding filler materials or replacing welding by brazing [9]. It makes application of laser welding without filler desirable.

In manufacture of a range of aerospace engineering items using welding, the problem of sealing the inner cavities and compartments, containing electronics components, is solved. In these cases, it is necessary to both ensure sealing of such compartments and to avoid residual deformations and stresses in the structure. For this purpose, it is necessary to use welding technologies, which ensure producing relatively narrow welds with local heat input. Total heating of the item after welding should not be higher than 100–120 °C. Such a problem is readily solved by laser welding application.

Thus, at selection of the parameters of laser welding of light alloys by a sealing weld, it is rational to focus on producing nonthrough thickness penetration of a shape close to a triangular one. Here, the weld should be made with minimum heat input without filler material application.

RESEARCH GOALS AND OBJECTIVES

The objective of the study is preliminary determination of the parameters of laser welding by a sealing weld with nonthrough thickness penetration of thin-walled flanges of cylindrical parts and boxlike items from light metals and alloys based on Be and Al, taking into account the postweld heating temperature.

The following problems are solved to achieve the defined goal:

- calculation-based determination of mode parameters of laser welding of light alloys based on Be and Al with a nonthrough thickness penetration;
- calculation-based determination of heating temperatures for small-sized laser-welded items based on Be and Al;
- experimental verification of the selected mode parameters of laser welding of samples from an aluminium alloy and their heating temperatures.

PREDICTION OF MODE PARAMETERS OF LASER WELDING OF HIGH-STRENGTH LIGHT ALLOYS

When producing thin-walled items by sealing welds, disc-shaped or rectangular flanges may be welded to cylindrical or boxlike structures from light alloys. The main parameters of these structures are given in

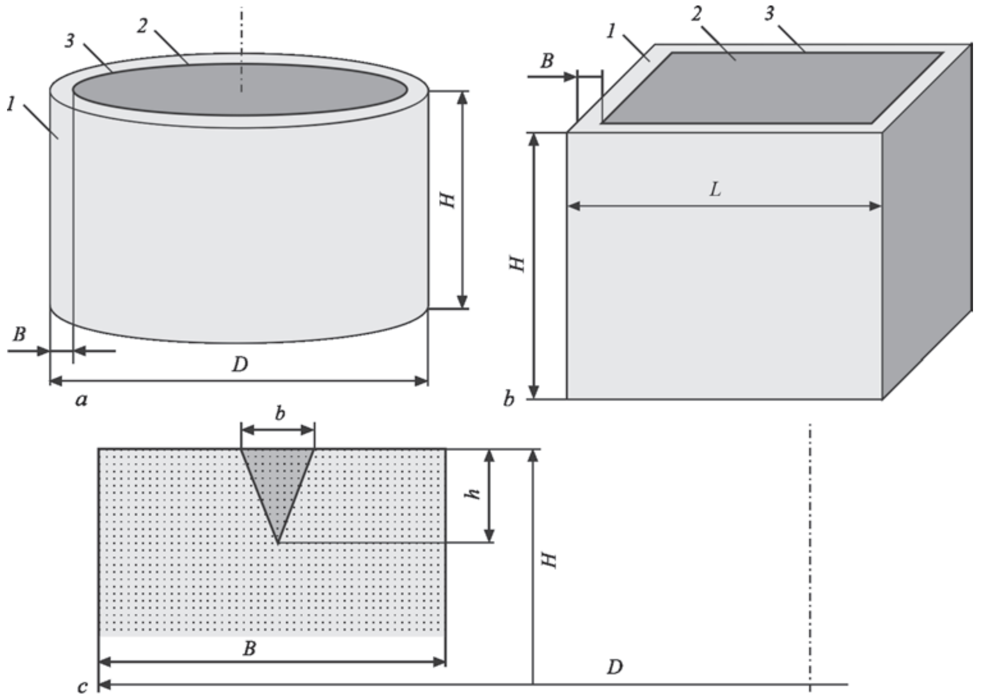


Figure 1. Geometrical parameters of the parts being welded and laser penetration (dark triangular region): *1* — case; *2* — flange being welded; *3* — weld

Figure 1. Let us consider two cases. In the first case, a disc flange of close thickness is welded to a cylindrical case of diameter *D*, height *H*, and wall thickness *B* (Figure 1, *a*). In the second case, a rectangular flange of a close thickness is welded to a boxlike structure of width *L* and height *H* (*L* = *H* variant) with walls of thickness *B* (Figure 1, *b*). In both the cases, the weld (simplified) has the form of a triangle with base *b*, which is the weld width, and height *h*, which is the penetration depth (Figure 1, *c*). To simplify the problem being solved we assume that: $D = L = H = 40$–50 mm, $B = 1.5$ mm.

To reduce the risk of appearance of residual deformations and hot cracking susceptibility, it is desirable to avoid increase of the temperature of part being welded above 100–120 °C. That is why we will divide the definition and solution of the thermal problem of welding the flange of a part from a beryllium (aluminium) alloy into two related, but rather autonomous tasks:

- selection of technological parameters of welding (heat source power, welding speed), proceeding from the geometrical dimensions of the weld;
- determination of temperature parameters of the part after welding.

SELECTION OF TECHNOLOGICAL MODE PARAMETERS IN LASER WELDING OF HIGH-STRENGTH LIGHT ALLOYS

At determination of laser welding parameters we will proceed from the fact that the masses of the cylindrical and boxlike parts are approximately the same. The parts are hollow in both the cases. Then, the mass of the part being welded, which is a hollow cylinder of diameter *D* with wall thickness *B*, is equal to:

$$m_{piece} = \frac{\pi}{4}\gamma H\left[D^2 - \left(D - 2B\right)^2\right], \quad (1)$$

while the weld mass

$$m_w = \pi\gamma\left(D - B\right)S_w, \quad (2)$$

where γ is the density of metal (beryllium or aluminium).

Figure 2 shows the dependencies of specific heat values of beryllium and aluminium on temperature *T* [10]. It should be noted that beryllium has the highest heat capacity among metals, which strongly depends on temperature. As one can see from Figure 2, *a*, the heat capacity values at room temperature and at melting temperature differ by approximately three times (area c_{solid}). Moreover, a jumplike decrease in heat capacity occurs at melting. Heat capacity of liquid beryllium is little studied; it is constant at temperatures a little higher than the melting temperature [10], i.e. it does not depend on temperature (area c_{liquid}). We will take it into account in the heat balance, by which we will describe the laser welding process.

All the energy, given off by laser radiation to the metal being welded, is spent for its heating up to the melting temperature, melting proper, liquid metal heating up to boiling temperature and partial evaporation of metal. The heat balance equation has the following form:

$$\left(1 - \beta\right)P_L = \gamma v S_w \times \\ \times\left[\int_{T_0}^{T_m} c_{solid}\left(T\right)dT + q_m + \int_{T_m}^{T_{max}} c_{liquid}\left(T\right)dT + \xi q_{ev}\right], \quad (3)$$

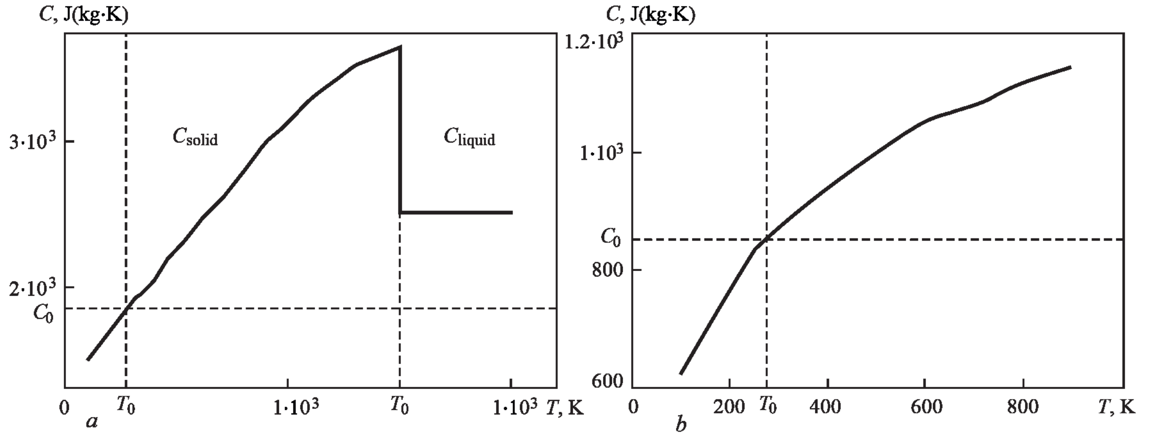


Figure 2. Dependencies of specific heat conductivity of beryllium (*b*) and aluminium (*a*) on temperature *T*: T_0 — ambient temperature; T_m — melting temperature; c_0 — specific heat under normal conditions, given in reference sources [10]

where P_L is the laser radiation power; β is the metal reflectivity; *v* is the welding speed; q_m and q_{ev} is the latent heat of melting and vaporization; ξ is the fraction of metal, which evaporated (usually, it is 3–5 %); T_{max} is the maximum temperature of metal heating.

Equation (3) was written for laser welding with a vapour-gas channel. Here, maximum temperature T_{max} is higher than the metal boiling temperature T_b by several degrees.

Using the heat balance equation (3), we can determine the technological parameters of welding, depending on the required weld dimensions. For instance, welding speed is determined by penetration depth and power of the laser, which is used

$$v = \frac{(1-\beta)P_L}{\gamma S_w \left[\int_{T_0}^{T_m} c_{solid}(T)\,dT + q_m + \int_{T_m}^{T_{max}} c_{liquid}(T)\,dT + \xi q_{ev} \right]}. \quad (4)$$

Formula (4) was used to calculate the dependencies of laser radiation speed on penetration depth at different power of laser radiation (Figure 3). They make it easy to select such an important technological parameter, as welding speed, to ensure the required penetration depth. Here, it is necessary to consider some limitations. So, at low speeds, the weld width can become greater than the item wall thickness, which is inadmissible. At high speeds, weld formation defects of the type of undercuts and lacks-of-fusion, may appear.

Figure 4 presents the dependence of laser welding speed on laser power at different penetration depths. The data in Figures 3 and 4 can be used to select the welding speed and radiation power, which allow achieving the required penetration depth, when ensuring the respective quality and tightness of the item.

Figure 4 shows the attractiveness of application of the technological modes of welding, with which the speed varies in the range from 30 to 70 mm/s, and laser power — from 500 to 2000 W for beryllium and from 300 to 1000 W for aluminium. Here, the process of laser welding is ensured without application of any additional technological measures or equipment.

Equation (3) allows determination of laser power, necessary to achieve the required penetration depth. Obviously, it is also determined by welding speed:

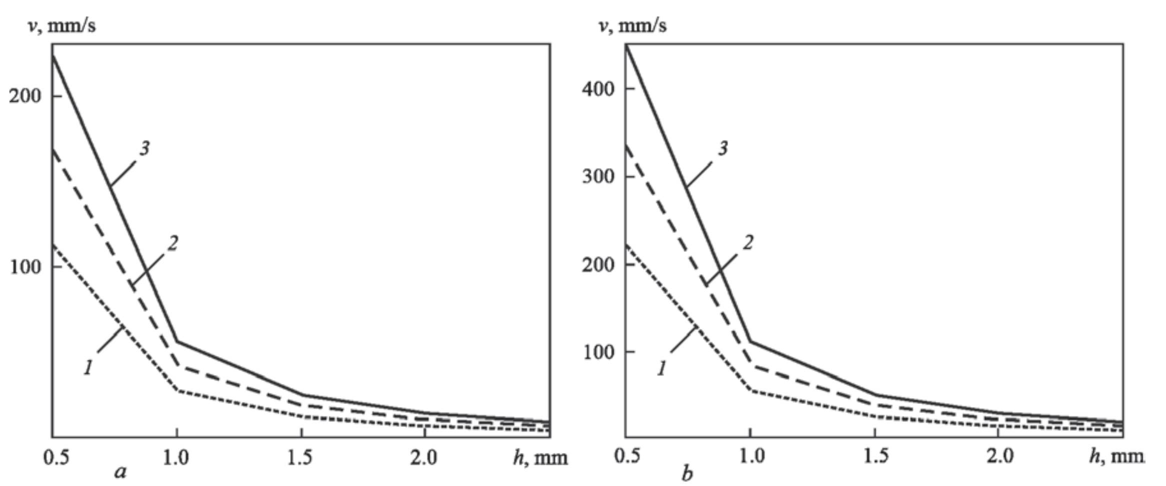


Figure 3. Dependence of speed *v* of laser welding of beryllium (*a*) and aluminium (*b*) on penetration depth *h* at different laser power P_L: *1* — *P* = 500 W; *2* — 750; *3* — 1000

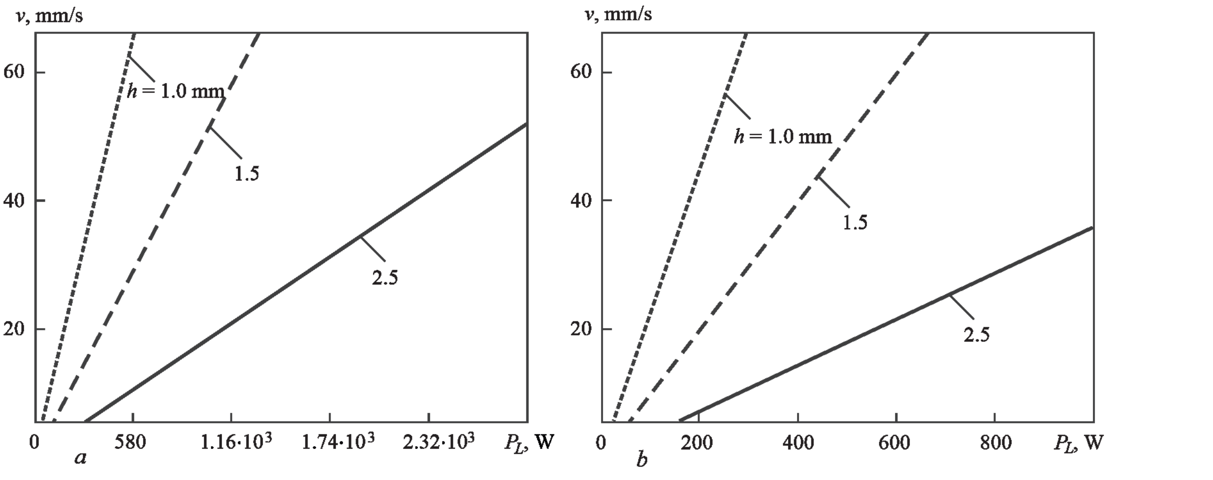


Figure 4. Dependence of speed *v* of laser welding of beryllium (*a*) and aluminium (*b*) on laser power P_L at different penetration depths *h*

$$P_L = \frac{\gamma v S_w}{1-\beta} \times \left[\int_{T_0}^{T_m} c_{solid}(T)\,dT + q_m + \int_{T_m}^{T_{\max}} c_{liquid}(T)\,dT + \xi q_{ev} \right]. \quad (5)$$

Figure 5 shows the dependencies of laser power on laser welding speed at different penetration depth. These dependencies allow determination of the ranges of radiation power, required for welding on flanges of δ ~ 1.5 mm thickness with nonthrough thickness penetration to cases with a not smaller wall thickness. For the case of welding beryllium alloys this is the range of 800–1200 W, for the case of welding aluminium alloys this is 400–800 W. Such power ranges allow welding at acceptable speeds, as well as covering rather wide ranges of penetration depths.

Figure 6 shows the dependencies of laser power on penetration depth at different laser welding speeds. These dependencies demonstrate that it is enough to apply an 800–1600 W laser for beryllium alloys and 400–1000 W laser for aluminium alloys, in order to ensure penetration with a guaranteed depth of 1.0–1.5 mm.

Thus, the proposed procedure allows making preliminary assessment of the technological parameters of the welding process, as well as selecting equipment (in particular, technological laser), which is necessary for realization of the process.

CALCULATION OF AVERAGE TEMPERATURE OF THE ITEM AFTER LOCAL HEATING DURING WELDING

In order to determine the part temperature after welding, we will proceed from the fact that the temperature of local heating of the item in the weld zone (dark triangular area in Figure 1) is much higher than that of the item. When the weld cools down its temperature and that of the item are equalized. If we denote average temperature as T_x, then the equation of energy balance has the following form:

$$m_w \left[\int_{T_x}^{T_m} c_{solid}(T)\,dT + q_m + \int_{T_m}^{T_{\max}} c_{liquid}(T)\,dT \right] = m_{piece} \int_{T_0}^{T_x} c_{solid}(T)\,dT. \quad (6)$$

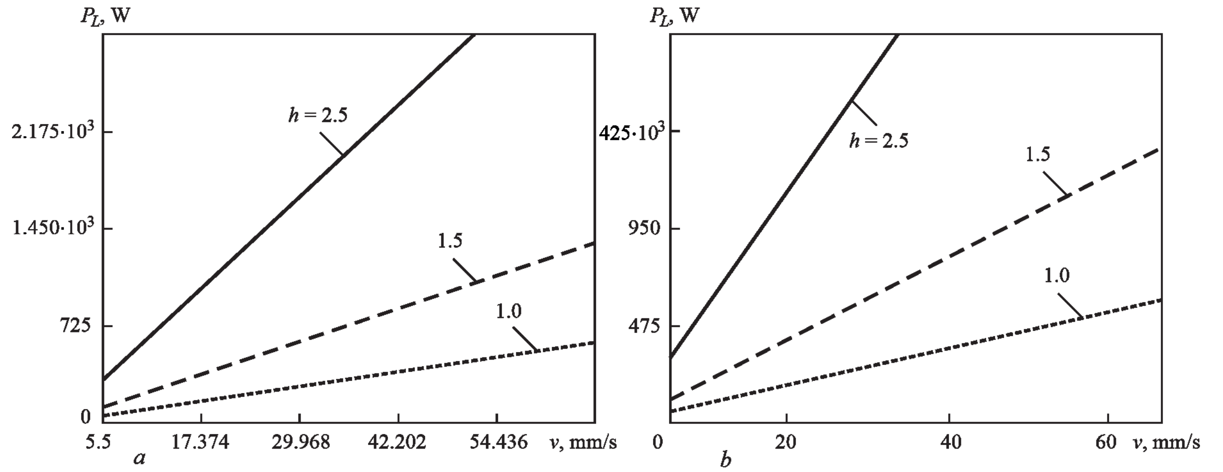


Figure 5. Dependence of laser power P_L on speed *v* of welding beryllium (*a*) and aluminium (*b*) at different penetration depths *h*

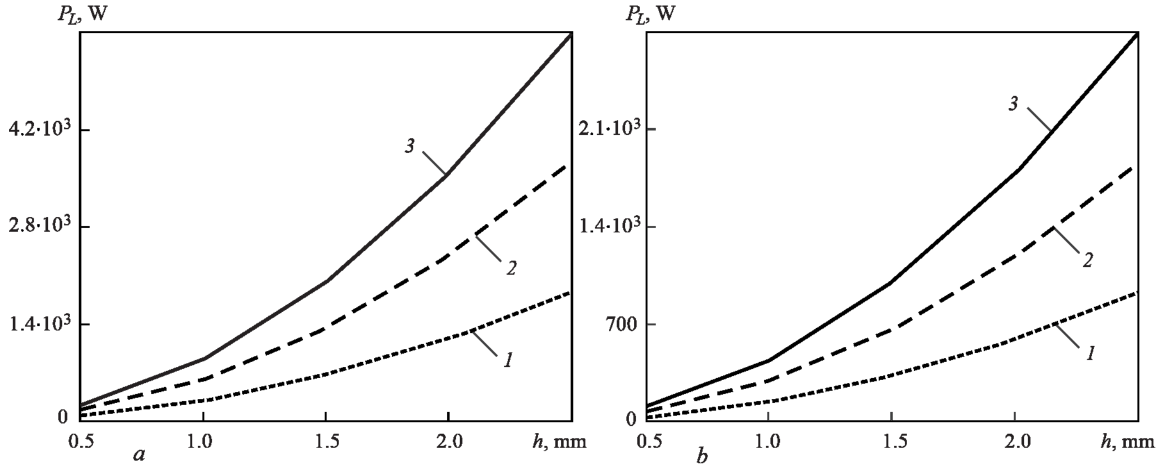


Figure 6. Dependence of laser power P_L on penetration depth *h* at different speeds *v* of laser welding of beryllium (*a*) and aluminium (*b*): *1* — *v* = 16.67; *2* — 33.3; *3* — 50 mm/s

In other words, the energy, evolving at cooling both of the liquid metal and the solidifying metal, together with the latent heat of melting, is consumed for heating the rest of the item from ambient temperature T_0 up to temperature T_x.

Equation (5) is nonlinear with the special feature that the unknown is included into it as the limit of integration of the determined integrals.

There are still no established procedures to solve such equations. Therefore, we modified the known methods of numerical solution of nonlinear equations. One of the problems arising when solving equation (6), was that of significant time losses at calculations. This was explained by the need to numerically determine the values of two integrals with a changing boundary at each iteration step. The situation was made more complicated by that the functions that are under the integral sign, were assigned by the table, i.e. by points. To achieve an acceptable accuracy, it was necessary to use cubic spline interpolation.

Therefore, calculations yielded a not very large data file (Tables 1 and 2), which are still enough for preliminary evaluation conclusions. Numerical experiments were conducted at the following constant parameters: part outer diameter *D* = 40 mm; part height *H* = 50 mm; ambient temperature T_0 = 27 °C; for Table 2 wall thickness *B* = 1.5 mm.

Analysis of the obtained results showed that it is possible to select the welding process parameters, which ensure such weld dimensions, at which item overheating above 100 °C is not reached. So, in welding thin-walled items (*B* = 1.5 mm) it is desirable for weld width not to exceed 1.5 mm.

Item wall thickness *B* and weld width *b* have the greatest influence on item heating. At selection of mode parameters, it should be taken into account that welding at higher speeds promotes reduction of weld width. Therefore, application of high-speed modes to reduce the average temperature of the item is promising.

EXPERIMENTAL VERIFICATION OF THE SELECTED PARAMETERS OF LASER WELDING

A laboratory set-up based on fiber laser of MFSC 2000W model (MAX Company, China) of up to 2000 W power was developed to perform experimental check-up. Radiation of this laser was focused by a welding head shown in Figure 7 into a spot of approximately 0.2 mm diameter by optics with 200 mm focal distance. Welding was performed with argon shielding with flow rate of 8–10 l/min. Only aluminium alloys were used in the experiments, to avoid the danger of poisoning by welding fumes. Aluminium alloys 7005 (1915) and 7075 of Al–Zn–Mg–Cu system were selected as sample materials. By their physico-mechanical characteristics these alloys are the closest to commercial beryllium-aluminium alloys of Be–Al–Mg system (Tables 3, 4). Flat and cylindrical samples with wall thickness *B* = 1.5 mm were made from these alloys. Flat samples of 50×50×1.5 mm size were welded by

Table 1. Dependence of average temperature T_x of the item on thickness *B* of its wall (weld width *b* = 1.0 mm)

Item wall thickness *B*, mm	Average temperature T_x (Be alloy), °C	Average temperature T_x (Al alloy), °C
1.0	88	83
1.2	80	77
1.5	74	71
2.5	63	61
3.0	61	59

Table 2. Dependence of item average temperature T_x on weld width *b* (item wall thickness *B* = 1.5 mm)

Weld width *b*, mm	Average temperature T_x (Be alloy), °C	Average temperature T_x. (Al alloy), °C
0.5	54	53
1.0	74	71
1.2	85	81
1.5	106	100
2.5	203	186

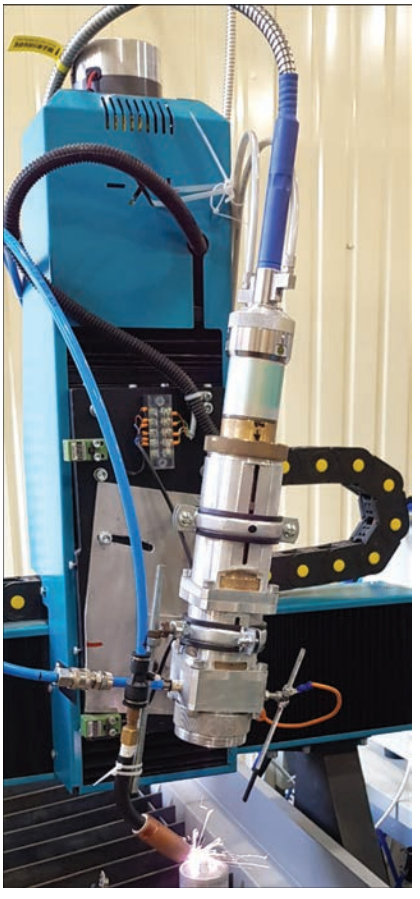


Figure 7. Laboratory stand for conducting experiments on laser welding of flanges by sealing welds with nonthrough thickness penetration of the thin-walled cylindrical item from an aluminium alloy

linear fillet welds, cylindrical samples of 40×50 mm size were joined by circumferential welds.

Welding of samples was performed using calculated parameters of the modes (Figures 3–6). So, in order to obtain joints with penetration depth $h \sim 0.6$ mm, in keeping with the data in Figure 3, *b*, it is recommended to select welding speed of 150 mm/s at laser radiation power $P_L = 500$ W. By the data of Figure 5, *b* a speed of 66.7 mm/s will be required at radiation power of up to 400 W. By the data of Figure 6, *b* at welding speed of 50 mm/s, the radiation power should be in the range of $P_L = 350 – 400$ W. Power $P_L = 400$ W and speed $v = 66.7$ mm/s were selected during experiment performance. A weld of depth $h \sim 0.6$ mm and width $b \sim 0.6$ mm was produced as a result (Table 5).

Thus, in keeping with Figures 3, *b*–6, *b* a number of mode parameters were selected, which were used to conduct experiments on laser welding. The modes and the obtained results (in the form of transverse macrosections of the welds) are given in Table 5.

Measurements of sample heating temperature were performed during performance of experiments on welding in the modes, given in Table 5 (Figure 8). Here, an infrared pyrometer of GM320 model (Benetech Shenzhen Jumaoyuan Science and Technology Co., Ltd., Shenzhen, PRC) with measurement range of –50–+380 °C and up to 1.5 °C error was used. Temperature measurements were conducted in the zone of welded structure side surface closest to the weld directly after completion of the welding process. Measurement distance was $Y = 300–500$ mm.

For instance, to produce welds with penetration depth $h = \sim 1.0$ mm, in keeping with the data of Table 5, welding was performed at speed $v = 58$ mm/s at 500 W radiation power. After welding, an optical pyrometer was used to measure the welded sample temperature. Performed measurements showed that temperature is within 70–75 °C that corresponds to the data of Tables 1 and 2 with up to 6 % error. Further experiments showed that the discrepancy between the calculated and experimental data on welded sample heating is not greater than 10 %.

Comparison of such calculated and experimentally established mode parameters, as power P_L and welding speed v, as well as penetration depth h, allows us to say that in keeping with the proposed calculation procedure the mode parameters of laser welding of light alloys can

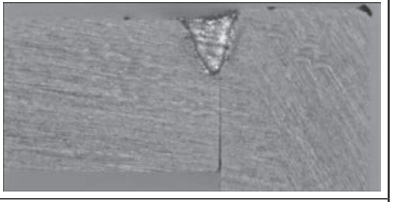
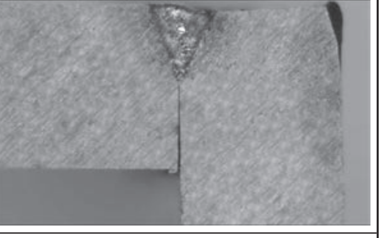
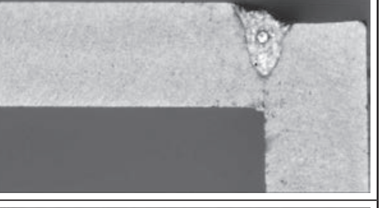
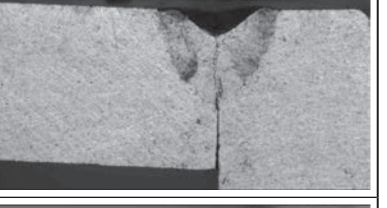
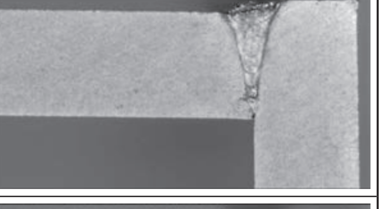
Table 3. Content of chemical elements (wt.%), used when studying the aluminium alloys and the examined beryllium alloy

Alloy grade	Al	Be	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other
7005 (1915)	Base	–	Up to 0.35	Up to 0.40	Up to 0.10	0.2–0.7	1.0–1.8	0.06–0.2	4–5	0.01–0.06	Zr 0.08–0.2; other up to 0.15
7075	Same	–	Up to 0.40	Up to 0.50	1.2–2.0	Up to 0.30	2.1–2.9	0.18–0.28	5.1–6.1	Up to 0.20	Up to 0.15
Lx-59-3	38	59	–	–	–	–	3	–	–	–	–
Lx-40-3	57	40	–	–	–	–	3	–	–	–	–

Table 4. Main physico-mechanical characteristics of the considered aluminium and beryllium-aluminium alloys (at normal temperature)

Alloy grade	Yield limit σ_y, MPa	Ultimate strength σ_t, MPa	Relative elongation, %	Young's modulus *E*, GPa	Density ρ, kg/m^3	Hardness *HB*, MPa
7005 (1915)	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 5. Comparison of calculated parameters of the modes with experimental results of laser welding of 7075 alloy

No.	Variants of calculated parameters of the mode /*h*	Experimentally established mode parameters /*h*, *b*	Error (by *h* parameter), %	Result (×30)
1	1) P_L = 300 W, *v* = 67 mm/s; 2) P_L = 500 W, *v* = 200 mm/s /*h* = 0.5–0.53 mm	P_L = 350 W, *v* = 67 mm/s /*h* = 0.51 mm; *b* = 0.5 mm	2–4	
2	1) P_L = 350 W, *v* = 67 mm/s; 2) P_L = 500 W, *v* = 150 mm/s /*h* = 0.55–0.6 mm	P_L = 400 W, *v* = 67 mm/s /*h* = 0.63 mm; *b* = 0.62 mm	5–15	
3	1) P_L = 500 W, *v* = 50 mm/s; 2) P_L = 750 W, *v* = 80 mm/s /*h* = 1.0 mm	P_L = 500 W, *v* = 58 mm/s /*h* = 1.1 mm; *b* = 0.86 mm	10	
4	1) P_L = 500 W, *v* = 42 mm/s; 2) P_L = 750 W, *v* = 66 mm/s /*h* = 1.2–1.3 mm	P_L = 500 W, *v* = 50 mm/s /*h* = 1.18 mm; *b* = 1.28 mm	2–9	
5	1) P_L = 500 W, *v* = 28 mm/s; 2) P_L = 750 W, *v* = 33 mm/s /*h*=1.3–1.5 mm	P_L = 600 W, *v* = 50 mm/s /*h* = 1.34 mm; *b* = 0.86 mm	3–11	
6	1) P_L = 500 W, *v* = 25 mm/s; 2) P_L = 750 W, *v* = 37 mm/s /*h*=1.5–1.6 mm	P_L = 650 W, *v* = 33 mm/s /*h* = 1.5 mm; *b* = 0.77 mm	2.5	

be determined with an up to 15 % error. Such an accuracy is acceptable in technological calculations.

DISCUSSION OF THE RESULTS OF FORMING LIGHT ALLOY JOINTS BY LASER WELDING

Conducted technological studies showed an acceptable level of error for the proposed calculation procedure. It can be assumed that the discrepancy between the calculated and experimental results is associated, in particular, with allowing for the base metal reflectivity β. This value depends both on metal heating temperature [11], and on the presence of an oxide film on the edges being welded, which absorbs the laser radiation much better than pure aluminium does [12]. Penetration of depth *h* ~ 1.18 mm (Table 5, item 4) is an example of it. In this case, a considerable increase of the remelted metal volume was observed, which is reflected in the weld widening without any significant increase in radiation power. Such an effect is attributable to lowering of radiation losses (β coefficient), because of penetration of Al_2O_3 oxide film into the weld pool.

Studies of welds made on 7005 and 7075 alloys showed that inner pores and cracks are the character-

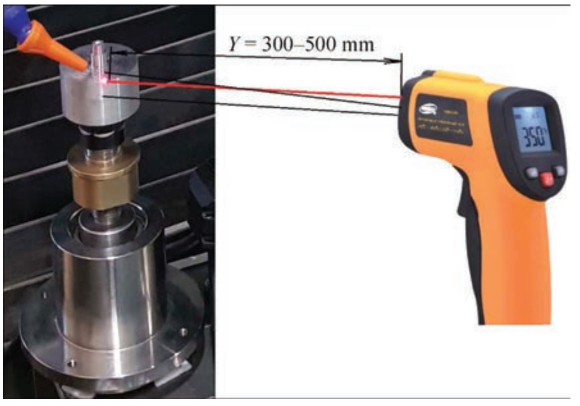


Figure 8. Scheme of measurement of sample heating temperature after welding by manual infrared pyrometer (dashed line visualizes the laser sight)

istic defects of their formation. Pores formed not in all the welds, but just in certain cases (for instance, Table 5, items 2 and 3). Their size is within 0.05–0.2 mm, and they are located mostly in the middle part of the weld. Pore location along the weld is irregular, and their spacing varies from 2.5 up to 50 mm and more (Figure 9). However, their formation sites predominantly coincide with the rolling bands of the welded sheets. We can assume that these pore formation are associated with penetration of fine particles of Al_2O_3 oxide film, as well as air, into the weld pool. The latter also comes in from the lower side of the butt being welded, which does not have gas protection. Cracks formed, predominantly at nonthrough thickness welding of 7075 alloy in the weld root part (see Table 5, item 4). The susceptibility to their formation becomes higher with increase of weld width. It is probable that the partial-penetration butt joint acts as a stress raiser that, combined with the residual stresses, promotes crack formation.

Rather accurate (with up to 10 % error) determination of the temperature of postweld heating of thin-walled items of the above-mentioned dimensions can be regarded as another confirmation of the acceptability of the proposed procedure. Comparison of the calculated results with some literature data was conducted to check the acceptability of the calculation procedure in welding beryllium alloys.

So, the data of welding 0.35 mm thick beryllium by pulsed Nd:YAG laser are given in work [13]. Welding was performed at the speed of 3.3 mm/s at radiation power density of 260 W/mm^2. For our case (fiber laser radiation which is focused into a 0.2 mm diameter spot), it corresponds to the power of ~ 10 W (taking into account the losses). It can be assumed that for welding 0.35 mm beryllium by radiation of power P_L ~ 100 W the welding speed is close to 33.33 mm/s, and for a thickness of 0.7 mm, P_L ~ 300 W and v = = 66.67 mm/s will be required. It follows from the graph in Figure 4, *a* that a speed of v ~ 66.67 mm/s is required for achieving a penetration of the order of 0.7 mm at power P_L ~ 300 W. From the graph in

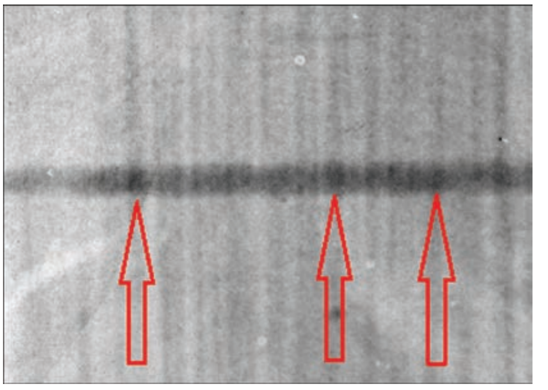


Figure 9. Detection of pores in welds by the results of radiographic testing (penetration in 7075 alloy sheet. made in the mode of item 3, Table 5)

Figure 5, *a* one can see that power P_L ~ 300 W is necessary to produce a penetration depth of the order of 0.7 mm at speed v = 55 mm/s. Thus, the discrepancy between the experimental and calculated values is less than 20 %.

Work [14] describes welding of beryllium alloys by electron beam process. Owing to a difference in pressure at electron beam and laser welding, their comparison is not quite correct. So, at laser welding the influence of low pressure atmosphere leads to increase of penetration depth by 10–20 % [15]. However, we will make such a comparison to obtain evaluation results. The following welding mode parameters were selected for electron beam welding of 1.5 mm plates: accelerating voltage U = 100 kW, beam current I = 7 mA, welding speed v = 8.5 mm/s. Here, the electron beam power density is ~ $14{\cdot}10^4$ W/cm^2 that corresponds to laser beam power of ~ 300 W. It can be assumed that at equivalent laser power of 600 W, the welding speed will be ~ 17 mm/s. We obtain similar data from the graph in Figure 6, *a*. Allowing for the difference in pressures, it can be assumed that the discrepancy between the experimental and calculated values is up to 20 %.

CONCLUSIONS

1. A procedure of calculation-based determination of the parameters of laser welding of thin-walled (up to 2.5 mm thick) items from high-strength light metals and alloys was proposed. Experimental verification on samples from aluminium alloys of 7xxx series of Al–Zn–Mg–Cu system and comparison with published data on beryllium alloy welding showed that the error of the proposed procedure is up to 15–20 %.

2. This procedure was used to select the main parameters of laser welding of a structure from 7075 alloy with 1.5 mm wall thickness by welds of 0.5–1.5 mm depth and 0.5–1.5 mm width. It was found that in welding by radiation of a fiber laser of up to 650 W power at not less than 33.3 mm/s speeds, minimal bulk heating of the items not higher than 100 °C is ensured.

3. Solving a nonlinear equation of heat balance allowed determination of the item postweld heating temperature with up to 10 % error.

4. Experimental studies showed that the characteristic defects of laser welding of aluminium alloys of Al–Zn–Mg–Cu-system are inner pores of 0.05–0.2 mm diameter and cracks in the weld root part at their formation with incomplete penetration. Pore formation may be related to air ingress into the weld pool from the side of the butt, and cracks can be associated with the butt acting as the notch — stress raiser, which promotes crack formation under the impact of residual stresses.

DEDICATION. The authors dedicate this study to the memory of Prof. V.M. Sydorets, Dr. of Science (Eng.) (PWI), owing to those works it was performed.

The work was performed with the support of the following projects:

1. The National Key Research and Development Program of China — in the framework of the strategy "One Belt — One Road" (grant number 2020YFE0205300);

2. Strategic project of the Academy of Sciences of Guangdong Province (GDAS "Project of Science and Technology Development, 2020GDASYL-202030100), China;

3. Project of the Guangdong Economic and Technological Development Zone 2019GH19, China.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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SUGGESTED CITATION

V.M. Korzhyk, V.Yu. Khaskin, S.I. Peleshenko, A.A. Grynyuk, Dong Chunlin, E.V. Illyashenko, Yuhui Yao (2022) Selection of parameters of laser welding of thin-walled items from light alloys with nonthrough thickness penetration. *The Paton Welding J.*, **5**, 16–25.

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Received: 14.04.2022
Accepted: 08.08.2022