STUDY ON THE EFFECT OF INDUCTION HEATING TO PREVENT HOT CRACKING DURING LASER WELDING OF ALUMINUM ALLOYS

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This work is devoted to research of hot spots generated by induction heating to prevent hot cracks during laser welding of Al–Mg–Si and Al–Si aluminum alloy samples 2 mm thick. The results of numerical modeling of temperature fields and stress fields formed during the process of induction heating, as well as results of experimental validation of the simulation are shown. 25 Ref., 3 Tables, 10 Figures.

Keywords: *laser welding, induction heating, aluminum alloys, modeling, SYSWELD, thermal stresses, hot cracks*

Aluminum alloys are widely used in various fields of engineering due to their good strength characteristics in combination with low weight [1]. Thus, they have a competitive advantage compared to other materials used in industry. They are also highly resistant to corrosion [2]. It is advantageous to use the insertion of heat-treated aluminum alloys in lightweight constructions as that can reduce the total weight of the product while maintaining its strength. Usage of aluminum welded structures manufactured via the method of butt joints is significantly limited due to its ability to form cracks during the welding process [3, 4].

Today, modern lasers such as fiber ones are increasingly used to welding aluminum products. They provide a relatively high penetration with low heat input [5], reduce the strain and minimize further processing, reducing the stages of production. In laser welding of aluminum alloys, similar problems related to their ability to form cracks occur, and high-rate cooling of melt during welding process is one of the cause of cracking.

The aim of the research was to prevent the formation of hot cracks in the aluminum alloys during laser welding. Our task is to create the heating fields in the HAZ by two coaxial coils, that will create a stress field in the weld pool, which will reduce hot cracking.

Study of hot cracking during laser welding of aluminum alloys. Hot cracks are the brittle intercrystalline fractures of the weld metal and HAZ formed in the solid-liquid state at the finish of crystallization, and also in the solid state at high temperatures at the stage of the main development of intercrystalline deformation.

Cracks in aluminum materials are mainly formed during solidification of the weld metal caused by shrinkage and eutectic phase crystallization in the middle of the weld [6]. Pellini and then Clyne and Davies in their studies argue that the susceptibility to hot cracking in alloys of these groups is related to the «critical interval» that is the distance between oppositely directed growing dendrites during crystallization of the weld [7]. Feurer suggested that cracks are formed in the «soft» (quasi-equilibrium two-phase) zone if the rate of cooling of the interdendritic liquid is less or equal to the rate of shrinkage [8]. The approach to cracking of Piwonka and Flemings is based on the Poiseuille's equation which describes how the pressure gradient causes the fluid to flow in an «interdendritic way» [9].

All these theories are related to the peculiarities of crystallization of alloys. The susceptibility to hot cracking can be determined by obtaining the cooling curves for thermal calorimetry. Typical S-shaped curves test some binary alloys. The susceptibility to cracking is caused by the content of dissolved elements. The first quantitative description of the crack formation was proposed by Prokhorov in the middle of 20th century [10–12]. Prokhorov argued that mechanical tensile strain is a cause of cracking. He did not take into account the metallurgical condition in the «soft zone» and did not consider the microstructural formation during solidification of the two-phase region. Prokhorov did not quantify the criteria for predicting susceptibility to cracking. Most of the studies on solidification cracking in welds are based on the approach of Prokhorov, but they do not consider the accumulation of strain and defects of microstructure. These criteria only consider some of the mechanical conditions, such as critical stresses or strain rate.

Rappaz [13] and other authors describe the cooling of the interdendritic liquid and solid tensile strains as normal to the direction of the growth of dendrites. In their opinion, hot cracks are formed by cavitation pressure above a critical value of stress. It can be calculated according to the physical-chemical properties of alloy and microstructural dimensions of material. The possibility of hot cracking during welding has traditionally been measured for every individual case when the stress or deformation changes occur during the process. For example, Coniglio based his research on the concept of weldability. He believes that the susceptibility to cracks is determined by the critical rate of deformation during welding and studied the dependence of crack formation on content on silicon in aluminum alloys [14].

Recently, two models of the formation of cracks have come up. They are based on integration of the cracking localization. The first of these model was proposed by Shibahara [15, 16], who proposed to build it on the physical mechanism of crack formation according to fracture mechanics of solids. The value of stresses in liquid-solid phase was taken as criteria for the formation of cracks. He used the special computer equipment and finite element method for modeling of cracking. The assumption of the existence of metallurgical conditions in the two-phase region is not taken into account. Stresses in the system are compared with the stress critical value obtained in advance by the correlation with the melt surface energy. Surface energy is the known quantity and has the unique value for the temperature. Shibahara considers this as an aspect which generates local cracks. This approach has the following disadvantages:

- experimental determination of the surface energy at high temperatures is a very complex task;
- surface energy of the melt is strongly influenced by any changes in the chemical composition;
- very small amount of surface active element in the melt can lead to excessive change in the surface energy more than 10 times;
- calculated stress in the two-phase region is sensitive to mechanical properties at high temperatures. Large systematic errors were detected in measurements on the basis of such properties as yield point. Subsequently, it can lead to significant errors in the calculation.

The second approach of modeling cracks was developed by Hilbinger [17–19]. It is based on the theory of Pellini and is implemented using the finite element method as in the previous approach. Localization of tensile stresses in the liquid film in the rest of the melt is taken into account by introducing a «liquid» element in the middle of the weld. These elements have a very low flow in the liquidus–solidus temperature range. As criteria for crack formation the maximum allowable deformation of the «liquid» element in the two-phase region is taken. Critical deformation parameters are established experimentally. The approach of Hilbinger, as well as the method of Shibahara, gives a visual representation of the origin and propagation of cracks.

So, according to theoretical ideas, hot cracks are formed at critical values of the combination of the following factors:

- temperature interval of fragility (TIF) during solidification of the weld metal;
- minimum plasticity in the TIF, δ_{min};
- high rate of welding deformation α [20].

Literature data show several ways to prevent the formation of hot cracks in laser welding. For example, addition of filler material, preheating of samples in the furnace, using protective flux during welding, preheating by parallel laser of smaller capacity to compensate the tensile stresses in weld. Magnetic field also affects the process of laser welding. As was already said, the depth of penetration can be increased, cross-section can be changed, and periodic humping-type defects in weld can be suppressed by the magnetic field [21].

The use of induction heating during laser welding has a positive effect on the technological strength of the weld. It improves the weld geometry, regulates the keyhole shape and reduces the ability to form hot cracks and other defects in weld at crystallization [22].

Modeling the process of induction heating of aluminum alloy plates. The use of computer for process simulation very often promotes cost reduction in the development of defect-free technologies sharply by reducing the amount of experimental investigations. In manufacturing today, there is also the need to create algorithms with an optimal mode of parameters for laser welding on the basis of computer models of the process, which allows obtaining welds without defects [23]. In our investigations before beginning the experiments, the process was simulated

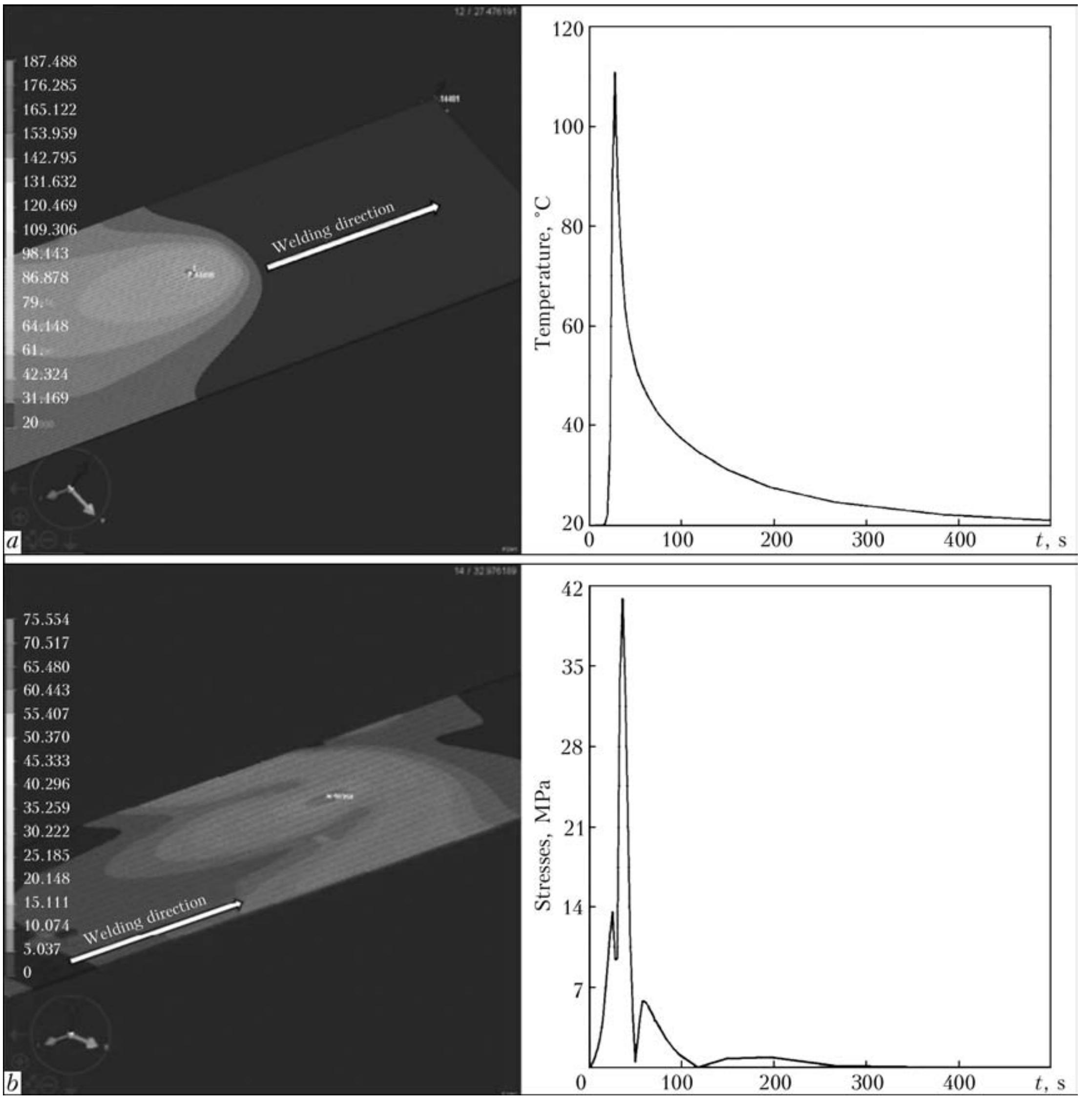

Figure 1. Example of calculated fields: *a* — temperature; *b* — stresses that occur in the sample during induction heating

by the computer program package SYSWELD 2012. Many different software packages and modeling tools exist currently. They are divided into specialized and universal programs. Specialized packages are used in the simulation of a limited number of systems and processes. Universal programs are in most cases commercial developments. With their help, it is possible to fulfill a wide range of applications, modeling a large number of physical processes and systems with complex geometry. One of these is the universal program SYSWELD.

SYSWELD is the software package that implements a finite element calculation scheme. It is used in static and dynamic analysis of structures subjected to physical and geometrical problems (2D and 3D problems). SYSWELD also solves the problem of linear and nonlinear stability of structures; simulates electromagnetic fields, hydro-gasdynamic, acoustic, and other processes.

The main objective of the research was to improve the technology of laser welding of aluminum alloys by preventing or reducing the formation of hot cracks. This was achieved by thermally induced compressive stress in the weld area. This was generated by induction heating on the plate surface, running parallel with the laser welding.

In the course of the simulation of the heating of the samples, the level of emerging internal thermal stresses was monitored [24].

The temperature and thermal stress fields, arising as a result of induction heating of the samples, were investigated with the help of numerical models created in SYSWELD. When building the model, it was taken into account that the efficiency of the setup for traditional method of induction heating of metal parts in a variable electromagnetic field does not exceed 60 % [25]. The process of induction heating from one side of the aluminum alloy plate in the course of its movement was modeled. The preparation

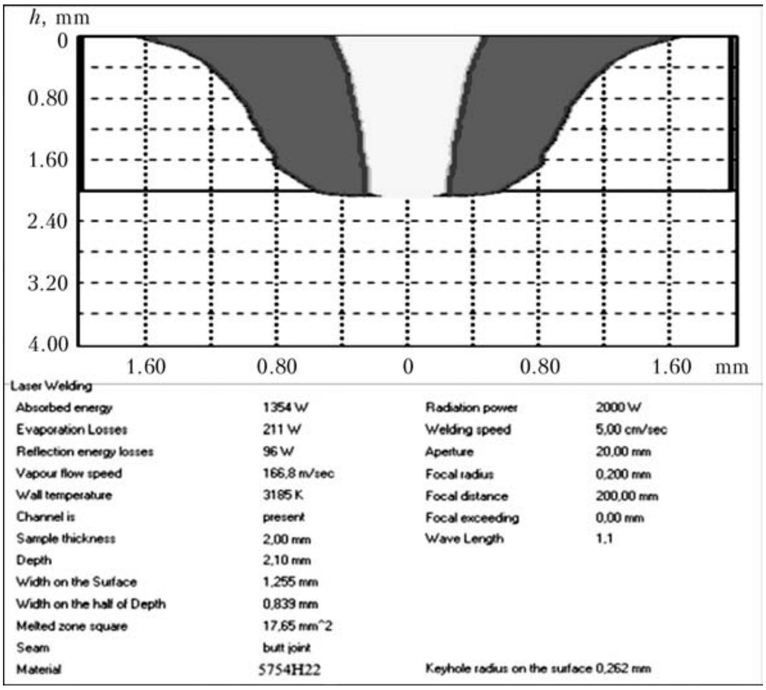

Figure 2. Results of simulation of laser welding of the 5754-H22 Al–Si alloy by software package LaserCAD

of the file for the calculation included the creation of 3D geometrical model of the sample with characteristics of the induction heat source, cooling modes, conditions of fixing and parameters of the heating process. The results of calculation were two files. The first file shows how the temperature field changes in time. The second file demonstrates the chronological variation of the stress fields. An example of results of the calculation of temperature and stress fields that occur in the sample with induction heating is presented in Figure 1.

As the bottom border of required temperature stress, the limit of elasticity was selected. Plastic deformation of the metal begins when the stresses are equal to the elastic limit which for aluminum alloys is more than 30 MPa. The main objective of the study was to obtain the parameters of induction heating at which in the near-weld zone the thermal stresses will compensate the tensile stresses in the weld. Then the results of the simulation were validated experimentally.

The laser welding process has been modeled, and optimal parameters of the full penetration of the plate are determined. Simulation was carried out using the software package LaserCAD

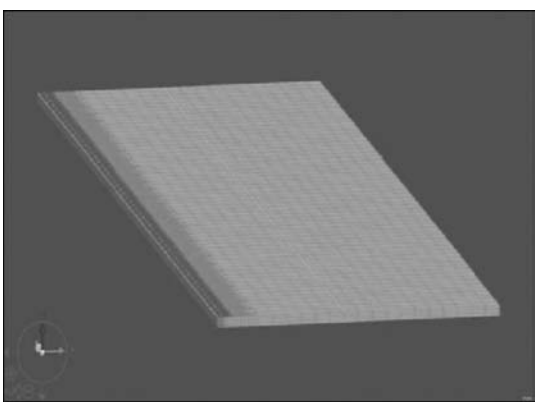

Figure 3. 3D geometrical model of laser welding of the 6082-T4 Al–Mg–Si alloy 2 mm thick with induction heating of HAZ built in software package SYSWELD 2012

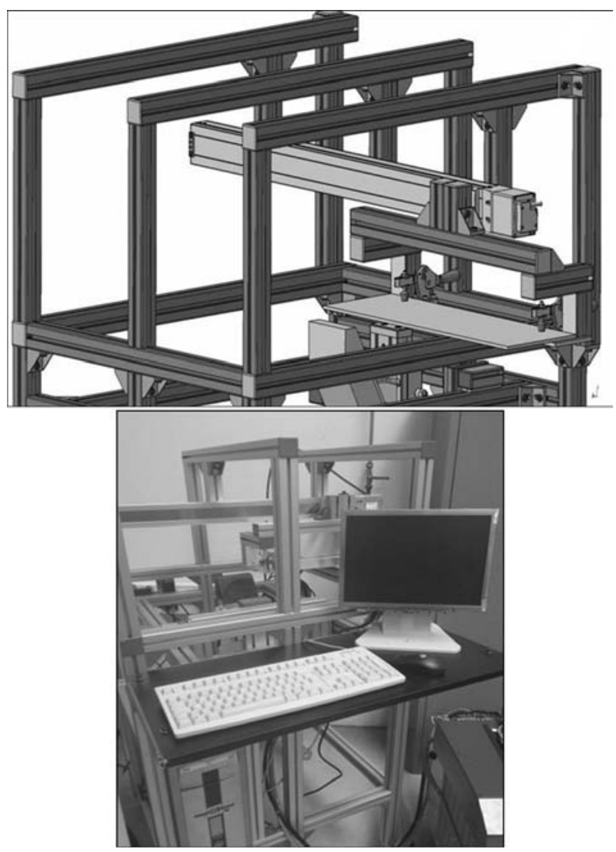

Figure 4. Experimental stand used

Table 1. Chemical composition of investigated aluminum alloys according to GOST 4784–97, wt.%

Alloy	Russian analogue	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
5754	AMg3	0.5–0.8	0.5	0.1	0.3–0.6	3.2–3.8	0.05	0.2	0.1	Others
6082	AD35	0.7–1.3	0.5	0.1	0.4–1.0	0.6–1.2	0.25	0.2	0.1	Same

Table 2. Mechanical properties of aluminum alloys investigated

Alloy	Type of processing	$\sigma_{0.2}$, MPa	σ_t, MPa	σ_{sh}, MPa	δ, %	*HV*
6082	T4	170	260	170	19	75
	T6	310	340	210	11	100
	0	60	130	85	27	35
5754	0	100	215	140	25	55
	H22	185	245	150	15	75
	H24	215	270	160	14	80

developed at the St.-Petersburg State Polytechnic University. An example of the simulation results is shown in Figure 2.

In the future, it is also planned to model the process of laser welding with induction heating by two inductors located at equal distance to the weld. To reduce the necessary computing power and calculation time the process will be simulated only for half of the weld. The image of the 3D geometrical model is presented in Figure 3.

Materials and experimental research. In the experiments, flat samples of 600 × 150 × 2 mm in size from Al–Si–Mg–Mn alloys AA6082-T4 and Al–Mg alloy AA5754-H22 were used. Chemical composition and mechanical properties of the materials are presented in Tables 1 and 2. Before experiments, the plates were cleared from grease and dirt with acetone.

The specially designed experimental stand was used for this study (Figure 4). It has the IFF GmbH coaxial inductor KI-112-U-30° (Figure 5). The components of the stand and their characteristics are presented below:

Maximum travel speed of the Oriental Motors linear drive with frame of stand built from aluminum profiles, mm/s 2000
The IFF GmbH equipment for induction heating
Pulse generator EW100W:
- maximum power, kW 10
- pulse power, % 0–750
- pulse frequency, kHz 8–20

Operating temperature of chiller, °C 18–30
Coaxial coil KI-112-U-30°:
- maximum time of process at maximum pulse power, s 0–100
- coil gap, mm 0.2–0.5
- heating temperature, °C 0–300

Figure 5. Coaxial coil KI-112-U-30° with pulse generator EW100W and chiller

The heated plates move at a speed equal to speed of welding, which was calculated with the help of computer simulation. Online measurements of the temperature in three different zones and measurements of the linear change of plate sizes were made during the experiments. The change of temperature was recorded with the help of the Greisinger Electronic GmbH 2-channel temperature meter GMH 3250 and the Mastech

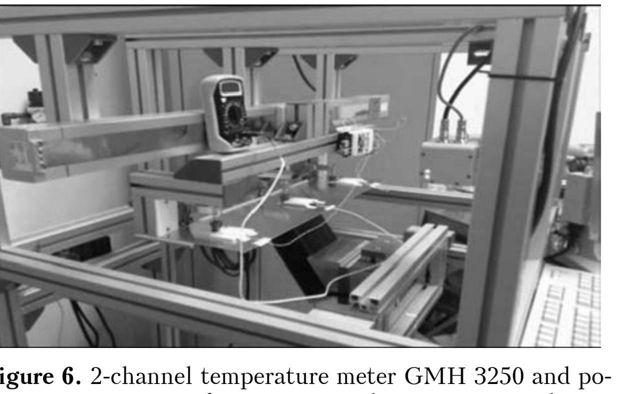

Figure 6. 2-channel temperature meter GMH 3250 and potentiometer IAS838 for measuring the temperature during induction heating of plate

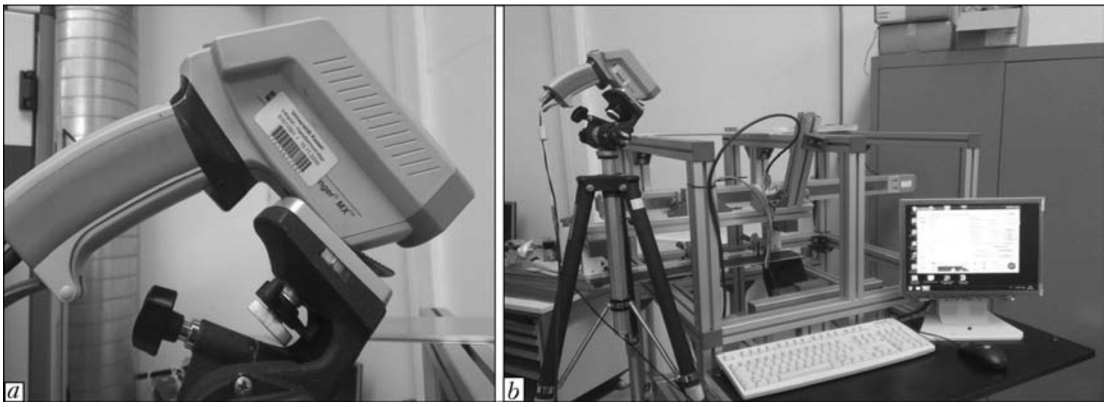

Figure 7. Infrared thermometer Raynger MX4 (*a*) for measurement of the temperature field (*b*)

potentiometer IAS838, functioning as a temperature measurement tool (Figure 6).

The temperature field movement was also registered via the Raytek GmbH high performance infrared thermometer Raynger MX4 (Figure 7). The images of the temperature fields, obtained in the course of the experiments, are presented in Figure 8.

In future it is planned to carry out an experimental verification of modeling results for laser welding using radiation generated from the IPG ytterbium fiber laser YLS 10000 with maximum output power of 10 kW (Figure 9). The movement of the beam will be carried out by the Reis Robotics robot (Figure 10).

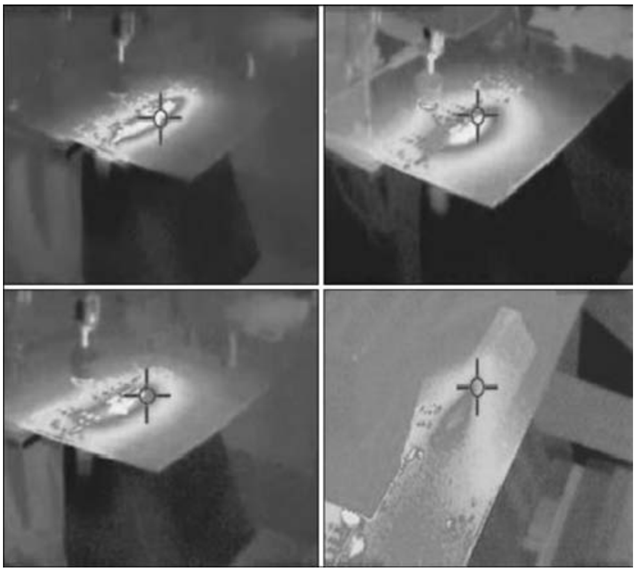

Figure 8. Images of temperature fields obtained

Figure 9. Ytterbium fiber laser YLS 10000

Some of the results of temperature measurements are given in Table 3.

As is seen from the Table, induction heating process parameters are divided into two stages: parameters of preheating the coil (step 1), and main parameters of heating the plate in movement (step 2). For induction heating the following parameters were chose from the results of simulation and experiments for step 1 and 2, respectively:

frequency of pulse in inductor f_1 = 12.5 and f_2 = 13.0 kHz; power of pulse in percentage of

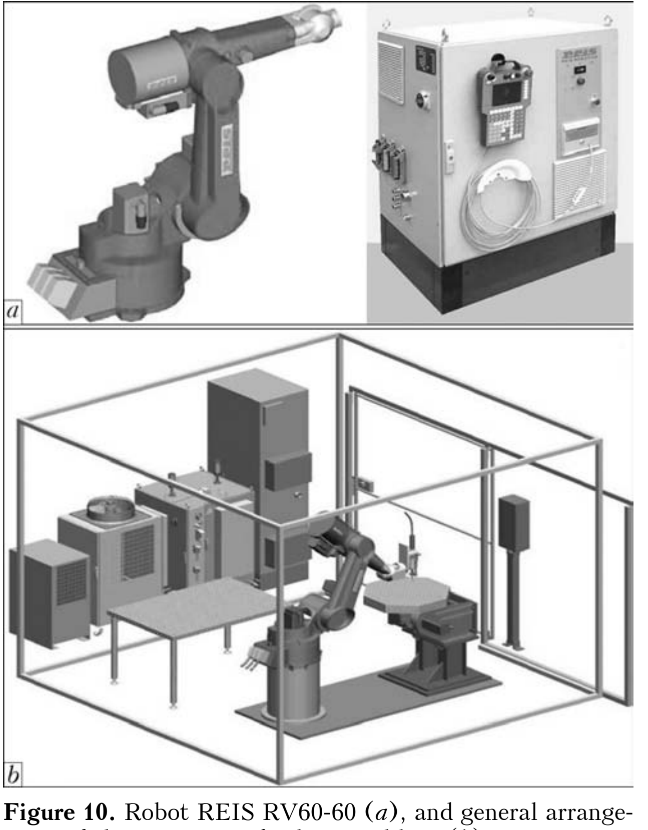

Figure 10. Robot REIS RV60-60 (*a*), and general arrangement of the equipment for laser welding (*b*)

Table 3. Results of experiments

№	Travel distance l, mm	T_{set}, °C	Regulation time, s	Step 1			Step 2			
				f_1, kHz	PWM_1, %	t_1, s	f_2, kHz	PWM_2, %	t_2, s	v, mm/s
1	500	300	1	12.5	750	10	13	600	10	50
2	500	300	1	13.5	750	10	15	700	10	50
4	500	300	1	12.5	750	10	13	600	10	50
5	500	300	1	12.5	750	10	15	600	10	50
11	483	300	1	12.5	750	5	15	700	10.5	50
12	483	300	1	12.5	750	5	13	700	10.5	50
13	483	300	1	12.5	750	5	13	700	10.5	50

Table 3 (cont.)

№	Direction of heating, and distance between inductor and welding line, mm	Gap before heating, mm			Temperature before heating, °C			Temperature during heating, °C		
		g_1	g_2	g_3	T_1	T_2	T_3	T_1	T_2	T_3
1	From right to left, 60	1	0.90	0.25	21.4	21.5	22	237.4	86.7	40
2	Same	1.50	1	0.70	35.2	28	25	246.2	93.9	53
4	From right to left to right, 60	0.50	0.50	0.50	23.1	24.4	26	297.8	86.6	52
5	Same	1	0.30	0.25	21.4	21.4	21	266.8	96.4	42
11	From right to left, 40	0.25	0.25	0.25	24	23.3	22.9	146	122.7	83
12	Same	0.25	0.25	0.25	26	24.9	23.7	143	141.3	97.4
13	»	0.25	0.25	0.25	28	27.1	25.4	144	142.7	97.8

generator maximum power PWM_1 = 750 and PWM_2 = 700 %; generation time t_1 = 5 and t_2 = = 10.5 s.

For step 1: the set of maximum of temperature generated T_{set} = 300 °C.

For step 2: the travel distance with movement l = 483 mm, v = 50 mm/s, gap between sheet and inductor before heating g = 0.25 mm. Recorded temperature was 100–140 °C. As result thermal stresses generated in welding were 38–50 MPa, that is similar to the results of computer simulation.

Results showed that the rate of heating up to high temperature depends on number of reheating of the sample. This is possible due to the change in material structure and its susceptibility to induction heating after heating up to higher than 140 °C. The closer the edge, the less power is needed for heating and generation of the necessary stresses. However, it is impossible to place the inductor closer to the plate edge because it will cause high rate deformations of the plate used. It is impossible to keep the constant parameters of heating the plate in process of its movement.

Conclusion

At this stage of research, the process of induction heating of the plates 2 mm thick of aluminum alloys AA6082-T4 and AA5754-H22 has been studied. Temperature and stress fields were simulated, and parameters of induction heating, creating thermal stresses in the plate and equal to stresses in the weld, were found.

It has been reported that the level of thermal fields depends on the heat source power at the stage of preheating and on the gap between the surfaces of the inductor and aluminum plates, and rate of heating depends on the impact and alloy original structure. Experiments, carried out at multiple induction heating with the subsequent air cooling after each heating of the plates, showed that after each heating process the average recorded temperature increased by a few degrees.

Authors thank the accompanying Ministry of Education and Science of the Russian Federation for his excellent support. The research was funded in the program «Michail Lomonosov» of DAAD and Ministry of Education and Science of the Russian Federation. This assistance is gratefully acknowledged.

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