Study on the Effect of Hot Spot Generated by Induction Heating to Prevent Hot Cracking During Laser Welding of Aluminum Alloys AA6082T4 and AA5754H22

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***Abstract*- This work is devoted to the research of hot spots generated by induction heating to prevent hot cracks during laser welding of aluminum samples. Plates were used, which were made from aluminum alloys AA6082T4 and AA5754H22 with a thickness of 2 mm. This article shows the results of numerical modeling of temperature fields and stress fields formed during the process of induction heating. The results of experimental validation of the simulation are also demonstrated.**

***Keywords*- Modeling; Sysweld; Induction Heating; Aluminum Alloys; Thermal Stress; Hot Crack**

I. INTRODUCTION

Aluminum alloys are widely used in various fields of engineering, due to their good strength characteristics in combination with their 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 aluminum constructions - as this can reduce the total weight of the product while maintaining its strength. The Usage of aluminum welded structures that are 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 are increasingly used to weld aluminum products, such as fiber-lasers. They provide a relatively high penetration with a low heat input [5].This reduces the strain and minimize further processing, reducing the stages of production. When laser welding aluminum alloys, similar problems related to their ability form cracks occur. The high - speed cooling of the melt during the laser welding process is one of the causes of the cracks.

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

II. STUDY OF THE PROBLEM OF HOT CRACKING DURING LASER WELDING OF ALUMINUM ALLOYS

Hot cracks are brittle in tercrystalline fractures of the weld metal and heat affected zone formed in the solid - liquid state at the end of the crystallization, and also in the solid state at high temperatures at the stage of the main development of the in tercrystalline deformation.

Cracks in the aluminum materials are mainly formed during the solidification of the weld, caused by shrinkage and by the crystallization in the eutectic phase in the middle of the weld [6]. Pellini and then Clein and Davis in their researches argue that the susceptibility to hot cracking in alloys of these groups is related to the “critical interval”. “Critical interval” is the distance between oppositely directed growing dendrites during the crystallization of the joint [7].

Foyrer suggested that cracks are formed in the “soft” (quasi-equilibrium two-phase) zone, if the rate of the cooling of the interdendritic liquid is less or equal to the rate of shrinkage [8].The approach to cracking of Pivonka and Fleming is based on the equation of Poysseul. It describes how the pressure gradient causes the fluid to flow in an “interdendritic way” [9]. All these theories are related to the method of the 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 [10]. The first quantitative description of the formation of cracks was proposed by Prokhorov in the middle of 20th century [11-13]. Prokhorov argued that mechanical tensile strain is a cause of cracking. He did not take into account the metallurgical condition in the “soft zone”. He did not consider the microstructural formation during the solidification of the two-phase region. Prokhorov did not quantify the criteria for predicting susceptibility to cracking. Most of the works on solidification cracking in welds are based on the approach of Prokhorov. But they do not consider the accumulation of strain and a defect microstructure. His criteria only consider some of the mechanical conditions, such as critical stress or strain rate. Rappatsa and other authors describe the cooling of the interdendritic liquid and solid tensile strain 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 stresses. It can be calculated according to the physical-chemical properties of the alloy and microstructural dimensions of the material [14]. The possibility of hot cracking during the welding process has traditionally been measured for every individual case when the stress changes during the process or deformations occur. For example, N. Coniglio based his research on the concept of weld ability. He believes that the susceptibility to cracks is determined by the critical speed of deformation during welding. He studied the dependence of the formation of cracks from the content of Si in the Al alloys [15].

Recently, two models of the formation of cracks have come up. They are based on the integration of the localization of the cracking. The first of these was proposed by Shibahara [16, 17]. He proposed to build on the physical mechanism of the formation of cracks in fracture mechanics of solids. The value of stresses in a liquid-solid was taken as criteria for the formation of cracks.

He used a special computer equipment and the method of finite element for the modeling of cracking. The assumption of the existence of metallurgical conditions in the two-phase region is not taken into account. The stresses in the system are compared with the critical value of stress obtained in advance by the correlation with the surface energy of the melt. The surface energy is a known quantity. It has a unique value for the temperature. Shibahara considers this as an aspect which generates local cracks. This approach has several disadvantages:

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

The second approach of modeling cracks was developed by Hilbinger [18-20]. It is based on the theory of Pellini. Modeling of hot cracking as in the previous approach is implemented using the method of finite element. 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 temperature range of liquidus – solidus. As criteria for the formation of cracks 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.

If we try to summarize the theoretical ideas that hot cracks are formed at the critical values of the combination of the following factors, then this can be concluded:

- Temperature interval of fragility (TIF) the during solidification of the weld metal;
- Minimum plasticity in TIF, δ_{min};
- High rate of welding deformation α. [21]

Literature shows several ways to prevent the formation of hot cracks in laser welding. For example, the introduction of filler material, preheating of the samples in the furnace, using protective flux during welding, parallel laser preheating of smaller capacities to compensate the tensile stresses in the weld. The magnetic field also affects the process of laser welding. As was already said, the depth of the penetration can be increased, the cross-section can be changed, and periodic defects of the weld called humping can be suppressed by a magnetic field [22].

The use of the induction heating during laser welding has a positive effect on the technological strength of the weld. It improves the weld geometry, regulates the form of the keyhole and reduces the ability to form hot cracks and other defects in the weld by crystallization [23].

III. MODELLING THE PROCESS OF INDUCTION HEATING PLATES OF ALUMINUM ALLOYS

The use of the computer to simulate the process very often makes it possible to reduce the costs of 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 [24].In our investigations before beginning the experiments, the process was simulated 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 a 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 (two-dimensional and three-dimensional problems). SYSWeld also solves the problem of linear and nonlinear stability of structures; simulates electromagnetic fields, hydro-gas dynamic, 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 [25].

The temperature fields and thermal stress, 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 traditional method of induction heating of metal parts in a variable electromagnetic field, the efficiency of the setup does not exceed 60% [26]. The process of induction heating from one side of the plate of aluminum alloy in the course of its movement was modeled. The preparation of the file for the calculation included the creation of a 3D geometrical model of the sample with characteristics of the source of induction heating, cooling conditions, conditions of fixing and parameters of the heating process. The results of the calculation were two files. The first file shows the temperature field as it changes in time. The second file demonstrates the chronological variation of the stress fields. An example of the results of the calculation of the temperature fields and stresses that occur in the sample with induction heating is presented on Figure 1.

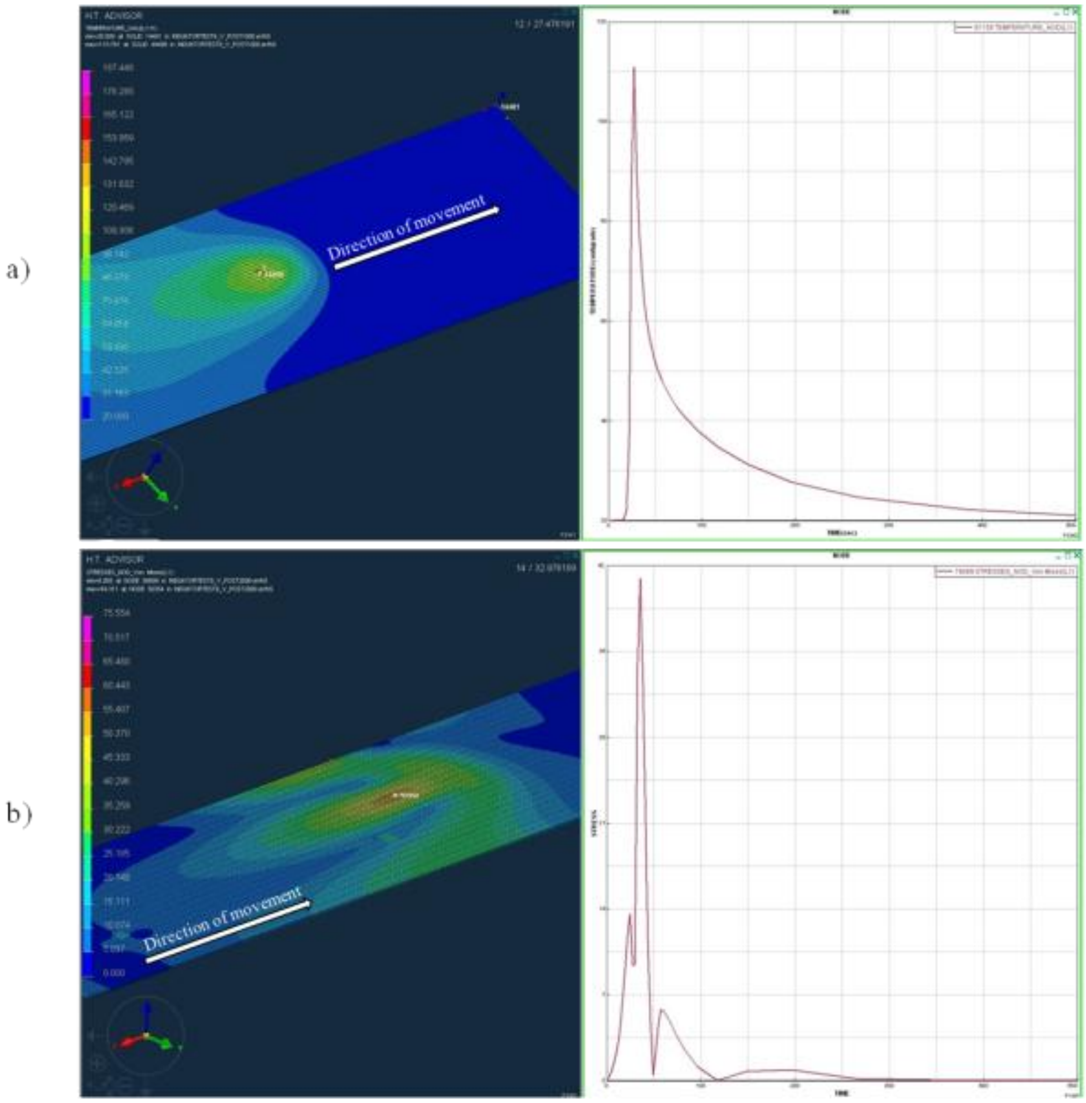


Figure 1 Example of calculated fields: a) temperature and b) stresses that occur in the sample during induction heating

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. The elastic limit for aluminum alloys is at more than 30 MPa. The main objective of the study was to obtain the parameters of induction heating under which, in the area near the welding, there are thermal stresses which will compensate for the tensile stresses in the weld. Then the results of the simulation were validated experimentally.

The process of laser welding has been modeled and optimal parameters of the full penetration of the plate are determined. Simulation was carried out using a software package Laser CAD, product of the St. Petersburg State Polytechnic University. An example of the simulation results for one of the types of materials is shown in Figure2.

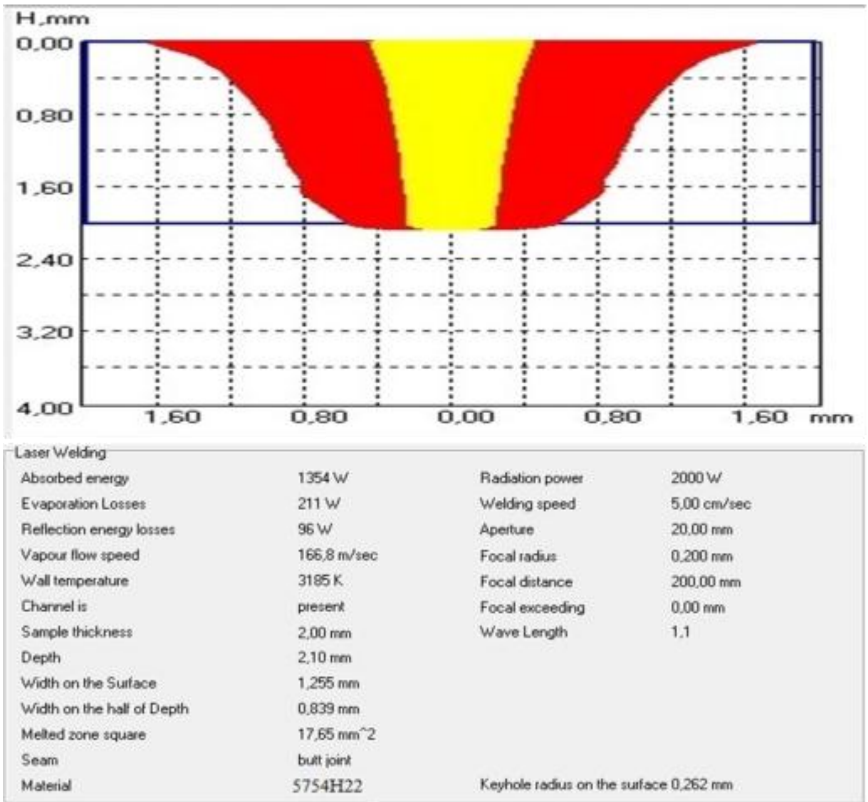


Figure 2 Results of the simulation of laser welding of aluminum alloy 5754H22by Laser CAD

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

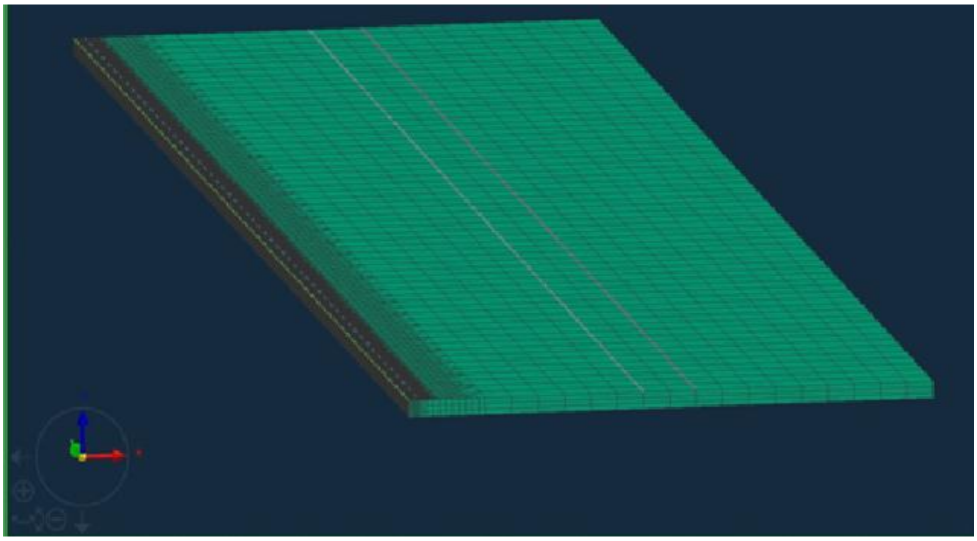


Figure 3 Image of the 3D geometrical model of the laser welding of the joints alloy 6082 T4
in the thickness of 2 mm with induction heating HAZ, built in SYSWeld 2012

IV. MATERIALS

In the experiments, flat samples were used with the dimensions 600*150*2 mm, two types of aluminum alloysAA6082T4 (AlSiMgMn) and AA5754H22 (AlMg) were used. Chemical composition and mechanical properties of the materials are presented in Tables I and II.

Before starting the experiments, the plates were cleared from grease and dirt with acetone.

TABLE I CHEMICAL COMPOSITION OF THE INVESTIGATED ALUMINUM ALLOYS ACCORDING TO GOST 4784-97

Alloy	Russian analogue	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other elements	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	-	Others

TABLE II MECHANICAL PROPERTIES OF THE ALUMINUM ALLOYS

Alloy	Type of processing	$\sigma_{0,2}$%, MPa	Tensile strength, MPa	Shear strength, MPa	Elongation,%	Hardness by Vickers, 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

V. EXPERIMENTAL RESEARCH

A specially designed experimental stand was used for this study (Figure 4). It has a coaxial inductor KI-112-U-30^{o}(IFF GmbH, - Germany), (Figure 5). The components of the stand, together with their characteristics are presented in Table III.

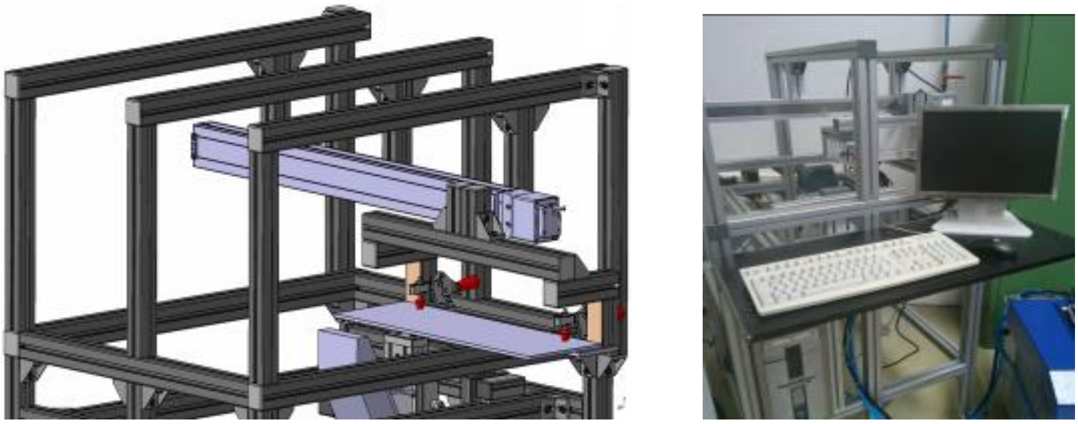


Figure 4 Images of the experimental stand

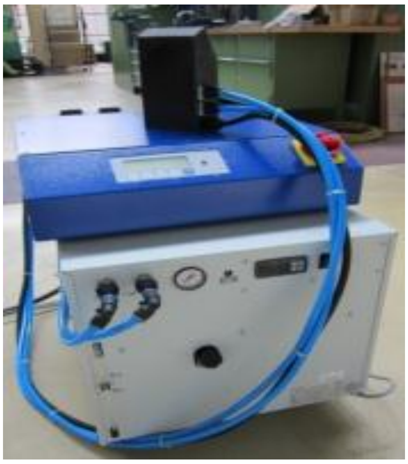


Figure 5 Image of the coaxial coil KI-112-U-30^{o} with a pulse generator and chiller EW100W

TABLE III COMPONENTS OF THE TEST BENCH TO INVESTIGATE THE EFFECT OF INDUCTION HEATING ON COMPRESSIVE STRESSES IN ALUMINUM ALLOYS

Components:	Range of parameters
1) *Linear drive* manufactured by Oriental Motors:	
Maximum travel speed, mm / sec,	2000
plus frame of stand, built from aluminum profiles	
2) *Equipment for the production of induction heating IFF GmbH:*	
Pulse generator EW100W:	
Maximum power, kW	10,0
Pulse power,%	0-750
Pulse frequency, kHz	8-20
Chiller: Operating temperature, o C	18-30
Coaxial coil Kl-112-U-30^o:	
Maximum time of process by using maximum power of pulse, sec	0-100
Gap for using coil, mm	0,2-0,5
Temperature of heating, ^{o} C	0-300

The plate heats up and moves at a speed equal to the speed of welding, which was calculated with the help of the computer simulation. Online measurements of the temperature in the three different zones and measurements of the linear change of the sizes of the plate were made during the experiments. The change of temperature was recorded with the help of 2-channel temperature meter GMH 3250 (Greisinger electronic GmbH, - Germany) and potentiometer IAS838 (Mastech), functioning as a temperature measurement tool (Figure 6).

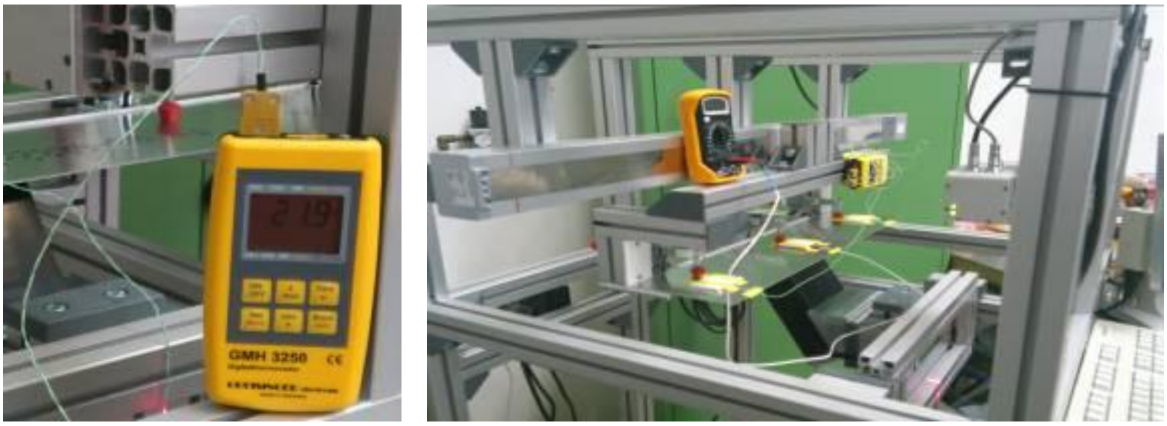


Figure 6 Image of the dual channel temperature meter GMH 3250 and the method of measuring the temperature during induction heating of the plate

The movement of the temperature field was also registered via infrared camera i60 (Flir Systems GmbH, - Germany) Figure 7.

Figure 7 Image of the infrared camera i60, product of the firm Flir Systems GmbH and the example of the measurement of the temperature field

The linear change of width of the sample and the curve during heating, were measured by the laser triangulation sensor Scan Control 2700-50(500) product of the firm Micro-Epsilon (Figure 8).

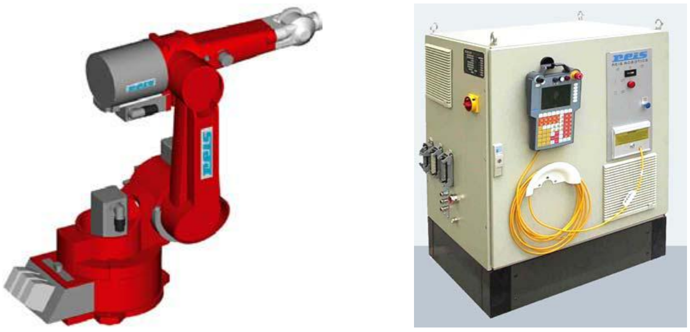
Figure 8 Image of the laser triangulation sensor

In future it is planned to carry out an experimental verification of modeling results for laser welding of the joints, using radiation generated from ytterbium fiber laser YLS 10000 with a maximum output power of 10 kW, product of the IPG (Figure 9).

Figure 9 Image of the ytterbium fiber laser YLS 10000

The movement of the beam will be carried out by a robot, product of the firm Reis Robotics (Germany) (Figure 10).

a)



b)

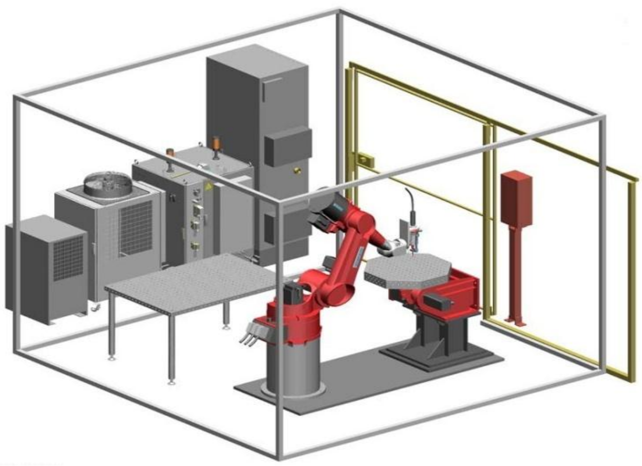


Figure 10 a) Image of the robot REIS RV60-60 (Reis Robotics, - Germany) and (b) the general arrangement of the equipment for laser welding

Some of the results of the temperature measurements are shown in Table IV.

TABLE IV RESULTS OF EXPERIMENTS

№	travel, mm	Tset, ^{o}C	Zeit reg. of T, sec	Step1			Step2				Direction of heating, distance between inductor and welding line	Gap before heating			T measuring before heating, ^{o}C			T measuring during heating, ^{o}C		
				f_1, kHz	PWM_1, %	$Zeit_1$, sec	f_2, kHz	PWM_2, %	$Zeit_2$, sec	V, mm/sec		gap_1, mm	gap_2, mm	gap_3, mm	T_1	T_2	T_3	T_1	T_2	T_3
1	500	300	1	12,5	750	10	13	600	10	50	From right to left , 60 mm	1,0	0,9	0,25	21,4	21,5	22	237,4	86,7	40
2	500	300	1	13,5	750	10	15	700	10	50	From right to left , 60 mm	1,5	1,0	0,7	35,2	28	25	246,2	93,9	53
4	500	300	1	12,5	750	10	13	600	10	50	From left to right, 60 mm	0,5	0,5	0,5	23,1	24,4	26	297,8	86,6	52
5	500	300	1	12,5	750	10	15	600	10	50	From left to right , 60 mm	1,0	0,3	0,25	21,4	21,4	21	266,8	96,4	42
11	483	300	1	12,5	750	5	15	700	10,5	50	From right to left , 40 mm	0,25	0,25	0,25	24	23,3	22,9	146	122,7	83
12	483	300	1	12,5	750	5	13	700	10,5	50	From right to left , 40 mm	0,25	0,25	0,25	26	24,9	23,7	143	141,3	97,4
13	483	300	1	12,5	750	5	13	700	10,5	50	From right to left , 40 mm	0,25	0,25	0,25	28	27,1	25,4	144	142,7	97,8

From the results of the simulation and the experiments, following parameters for induction heating were chosen:

Induction heating process parameters are divided into two stages:

1) process preheat coil: Step 1

2) the main parameters of the process of heating the plate in movement: Step 2

Step1: frequency of pulse in the inductor, f_1 *= 12,5 kHz, power of pulse in percentage of the maximum power of generator,* PWM_1*= 750%,*

generation time, $Zeit_1$ *= 5 sec, set the maximum of temperature generated,* T_{set} *= 300*^{o}*C.*

Step2: of pulse in the inductor, f_2 *= 13 kHz, power of pulse in percentage of the maximum power of generator,* PWM_2*= 700%, generation time,* $Zeit_2$*= 10,5 sec, travel with movement = 483 mm, velocity = 50 mm/sec, Gap between sheet and inductor before heating = 0.25 mm.* Recorded temperature was between 100 and 140 ^{o}C. This generates thermal stresses in during the welding process of 38 to 50 MPa. This is similar to the results of the computer simulation.

Results showed that the rate of the heating up to a high temperature depends on how often the sample is heated. This is possible due to the change in the internal structure of the material and its susceptibility to induction heating after heating up to the temperature of more than 140 ^{o}C. The closer to the edge, the less power is needed for the heating up and the generation of the necessary stresses. However, it is impossible to place the inductor closer to the edge of the plate, because it will cause high-speed deformations of the plate used in this case. It is impossible to keep the parameters of the heating up of the plate constant in the process of its movement.

The images of the temperature fields, obtained in the course of the experiments, are presented in Figure 11.

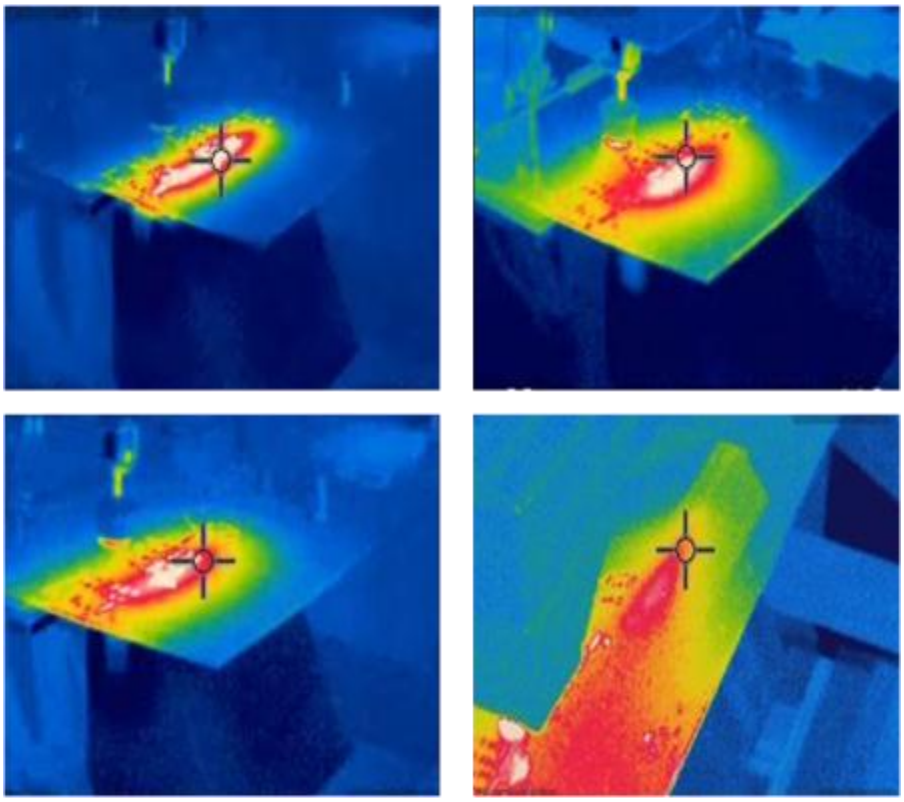


Figure 11 Images of the temperature fields obtained from experiments

VI. CONCLUSIONS

At this stage of research, the process of induction heating of plates made of aluminum alloys AA6082T4 and AA5754H22has been studied. The thickness of plates was 2 mm. The temperature fields and stress fields were simulated. Parameters of induction heating creating thermal stresses in a plate and equal value of stresses in the weld were found.

It has been reported that the level of the thermal fields depends on the power of the heat source at the stage of preheating and on the gap between the surfaces of the inductor and aluminum plates. The rate of the heating of the plates depends on the impact and the original structure of the alloy. Experiments have been carried out on multiple inductions heating plates with the subsequent cooling in air after each heating and showed that after each heating process the average recorded temperature increased by a few degrees. In future, experiments on laser welding together with induction heating are planned, in order to confirm the results of the simulation. Mechanical tests of the welded joints and metallographic studies of the structure of the weld will be made in further studies. The experiments on welding were transferred to 2013, as they are dependent on the specific equipment needed for these experiments.

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REFERENCES

[1] Lang, A. Schweißen von Aluminiumwerkstoffen im Fahrzeugbau. Jahrbuch Schweißtechnik. 1997, Bd. Jahrbuch Schweißtechnik; 1998.

[2] Ostermann, F.Anwendungstechnologie Aluminium. Berlin, Heidelberg: Springer-Verlag, 2007.

[3] Cam, G., dos Stantos, J.F. und Kocak, M.Laser and Electron Beam Welding of Al-Alloys: Literature Reviw. Geesthacht : GKSS-Forschungszentrum Geesthacht GmbH, 1997.

[4] Brune, Eberhard. Schweißer Maschinenmarkt. Schweissen von Aluminiumwerkstoffen. s.l.: Vogen Business Media, 2005. Bd. 106, 25/26.

[5] Thomy, C., Seefeld, T. und Vollertsen, F. Schweißen mit Hochleistungsfaserlasern. wt Werkstatttechnik. 2005, 10, 815 - 820.

[6] Ploshikhin, V., et al. Integrated Mechanical-Metallurgical Approach to Modeling Solidification Cracking in Welds. [Buchverf.] T. Böllinghaus und H. Herold. Hot Cracking Phenomena in Welds. s.l. : Springer Verlag, 2005.

[7] Clyne, T.W.; Davies, G.J. J. British Foundry, v. 74, p. 65, 1981.

[8] Feurer, U. Giessereiforschung, v. 28, p. 75, 1976.

[9] Piwonka, T.S.; Flemings, M.C. Trans. Metall. Soc. AIME, v. 236, p. 1157, 1966.

[10] Lara Abbaschian, Milton Sergio Fernandes de Lima, "Cracking susceptibility of aluminum alloys during laser welding", Materials Research,vol.6 no.2 Sro Carlos Apr. /June 2003.

[11] Prokhorov NN (1952) Hot cracking during welding (in Russian). Mashgiz, Moscow.

[12] Bochvar AA, Rykalin NN, Prokhorov NN, Novikov II, Movchan BA (1960). The Question of "Hot" (Crystallization) Cracks. Welding Production 10: 5–7.

[13] Prokhorov NN (1962) The Technological Strength of Metals While Crystallizing During Welding. Welding Production 4: 1–8.

[14] Rappaz, M.; Drezet, J.-M; Gremaud, M. Met. Trans., v. 30A, p. 449, 1999.

[15] Nicolas Coniglio. Aluminum Alloy Weld ability: Identification of Weld Solidification Cracking Mechanisms through Novel Experimental Technique and Model Development. - BAM-Dissertationsreihe Band 40.- Berlin 2008.- 208p.

[16] Shibahara M, Serizawa H, Murakawa H (2000) Finite Element Method for Hot Cracking Analysis under Welding Using Temperature Dependent Interface Element. In: Modeling of Casting, Welding and Advanced Solidification Processes IX (ed Sahm PR et al). Shaker-Verlag, Aachen, pp 844–851.

[17] Shibahara M, Serizawa H, Murakawa H (2001) Finite Element Method for Hot Cracking Analysis Using Temperature Dependent Interface Element. In: Mathematical Modeling of Weld Phenomena 5 (ed Cerjak et al). IOM Communications Ltd, London, pp 253–267Bergmann HW, Hilbinger RM (1998).

[18] Bergmann HW, Hilbinger RM (1998) Numerical Simulation of Centre Line Hot Cracks in Laser Beam Welding of Aluminum Close to the Sheet Edge. In: Mathematical Modeling of Weld Phenomena 4 (ed Cerjak). IOM Communications Ltd, London, pp 658-668.

[19] Hilbinger RM, Bergmann HW, Köhler W, Palm F (2001) Considering of Dynamic Mechanical Boundary Conditions in the Characterization of a Hot Cracking Test by Means of Numerical Simulation. In: Mathematical Modeling of Weld Phenomena 5 (ed Cerjak et al). IOM Communications Ltd, London, pp 847–862.

[20] Hilbinger RM (2000) Heißrissbildung beim Schweißen von Aluminium inBlechrandlage. Universität Bayreuth, Bayreuth.

[21] V. I. Vasil'ev, D. P. Il'yashenko, N.V. Pavlov. Introduction to the basics of welding. Tomsk, 2010, 338p.

[22] Dirk Lindenau.Dissertation: "Magnetisch beeinflusstes Laserstrahlschweißen."- Universität Stuttgart. Herbert Utz Verlag Wissenschaft. München. 2007.- 188 p.

[23] Gunther Göbel,Dr.-Ing. vorgelegte Dissertation Erweiterung der Prozessgrenzen beim Laserstrahlschweißen heißrissgefährdeter Werkstoffe.- Dresden. 2007.- 176 p.

[24] Rapoport E. Ya. Optimization of processes of induction heating of metal. - Moscow: Metallurgy. - 1993. - 279 p.

[25] A.G. Grigor' yants, I.N. Shiganov, A.M. Chirkov. Hybrid laser welding technology: handbook. - Moscow: Publishing House of the MSTU. NE Bauman, 2004. - 52.

[26] S.E. Korshikov, N.V. Zaikin, G.S. Rybalko. Simulation of temperature fields and thermal stresses during heating aluminum billets rotating in a magnetic field, DC. – 6p.