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MODELING THERMAL STATE OF STEEL PLATES WELDED BY LASER BONDING

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Abstract
The thematic justification of the material presented in this article includes such concepts as dynamism, limited time for mastering new products, obviousness, and digitization. All these concepts make the material expounded in this article substantially different from the previous publications [1-5]. This work aims to elaborate the procedure based on numerical evaluation of residual stress levels and, respectively, on forecasting structural strength and reliability. The latter property is largely determined by the precision in determining the thermal field in thermal influence areas. The proposed technique makes it possible to ensure precision required in engineering design and can be implemented as part of solving the non-standard heat conductivity task by the finite elements technique using modern CAE suites. The ultimate result of the implemented technology is the possibility to model thermal state of welded parts using modern CAE suitesnot on the samples but on the full-size finite-element model of thetestassembly, which allows arranging the solution of conjugate tasks in one finite-elements model. According to the calculated changes in the thermal field upon the welding of steel plates by laser bonding, the proposed model adequately describes the transmission of heat in the welding region. The attained results can be recommended for theproduct design and production engineering in mastering new small-size fine-mechanics products with high requirements on reliability in further operation
[3, 4, 6].
Key words: laser bonding, melt pool, non-stationary heat conductivity task, thermal field, finite elements technique

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INTRODUCTION

The research and methodological materials presented in this article ensure the scientific and practical application of such terms as dynamism, limited time for mastering new products, obviousness, and digitization. Previous studies [1-5] do not ensure the application of such complexes and, therefore, carry a much lower research and engineering significance. This work aims to elaborate the procedure based on numerical evaluation of residual stress levels and, respectively, on forecasting structural strength and reliability. The latter property is largely determined by the precision in determining the thermal field in thermal influence areas. The proposed technique makes it possible to ensure precision required in engineering design and can be implemented as part of solving the non-standard heat conductivity task by the finite elements technique using modern CAE suites. The ultimate result of the implemented technology is the possibility to model thermal state of welded parts using modern CAE suites not on the samples but on the full-size finite-element model of the test assembly, which allows arranging the solution of conjugate tasks in one finite-elements model. According to the calculated changes in the thermal field upon welding steel plates by laser bonding, the proposed model adequately describes the transmission of heat in the welding region. The attained results can be recommended for the product design and production engineering in mastering new small-size fine-mechanics products with high requirements on reliability in further operation[3, 4, 6].

MATERIALS AND METHODS

Despite the availability of developed laser bonding technologies, sometimes there is the need for controlling heat processes during welding. This has to do mainly with temperature restrictions in welding subassemblies with low heat-resistant parts, e.g., fluoroplastic sealants, parts with strict requirements on deviations in shape, structures sensitive to residual welding stresses that accelerate fatigue cracking at cyclic loads. If a material is susceptible to brittle destruction (low plasticity and impact viscosity, 3D stress state, usage in the thermal range of cold brittleness), its strength characteristics can be very much affected by residual welding stresses [7, 8]. In this regard, it is a topical task to elaborate techniques of modeling thermal state of component parts during laser bonding, i.e., model the conditions of residual stress formation in thermal influence areas.

The proposed modeling technique relies on solving the non-standard heat conductivity task in the 3D formulation by the finite elements technique. The motion of the heat source during welding is taken into account by successive nesting of heat along the seam length. For this purpose, the welded seam area in the design model is split in sections as a series of separate spaces the geometrical dimensions of which can be compared with the melt pool dimensions. The time of heat supply in each section corresponds to the time it takes the beam to pass the section length during welding.The space temperature in the course of heat supply corresponds to the temperature at the boundary between the melt pool and the main metal, i.e., to the melting temperature; the next phase is the cooling determined by the supply of heat to the metal and the environment. It is obvious that the precision of the calculated results will depend on the correctness of determining the melt pool parameters. The precision acceptable for determining these is ensured by the following relations [9 and 10] refined for laser bonding with incomplete fusion penetration of welded samples.

The amount of heat received by the metal per unit of time during welding (Jps) [11] is found as

$$q_H = \eta_H P \text{ ,(1)}$$

where η_H is the effective laser bonding efficiency dependent on the welding speed, physical chemical state of the parts surface, position of the optic system's focal plane relative to the welded parts. This indicator varies from 0.4 to 0.7 [11].

The melt pool length in meters is found as [3]

$$L = q_H / 2\pi\lambda_f T_L \text{ ,(2)}$$

where T_L is the metal melting temperature (^{0}C), λ_f is the in-liquid metal's heat conductivity (W/m*K).

The welded-through area width in meters is found as in [10]

$$B = 0{,}968\sqrt{\frac{q_H}{c_f \rho_f v T_L}} \text{ , (3)}$$

where c_f is the in-liquid metal specific heat capacity (J/kg*K), ρ_f is the in-liquid metal density (kg/m^3), and v is the welding (laser beam travel) speed (mps).

The melt pool has a complex shape with variable depth and cross-section area. In the proposed model, however, the welded seam fragment has a fixed height H corresponding to the maximal melt pool depth, i.e., to the fusion penetration depth.Given that the welded seam fragment has a constant isosceles trapezoid cross section (Fig. 1), the fusion penetration depth in meters is found as [4]

$$H = \frac{q_H}{2{,}2\pi T_L \lambda (L/B)} \text{ , (4)}$$

where λ is the solid metal heat conductivity at the temperature of crystallization (W/m*K).

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Thus the welded seam model will look like shown in Fig. 1.

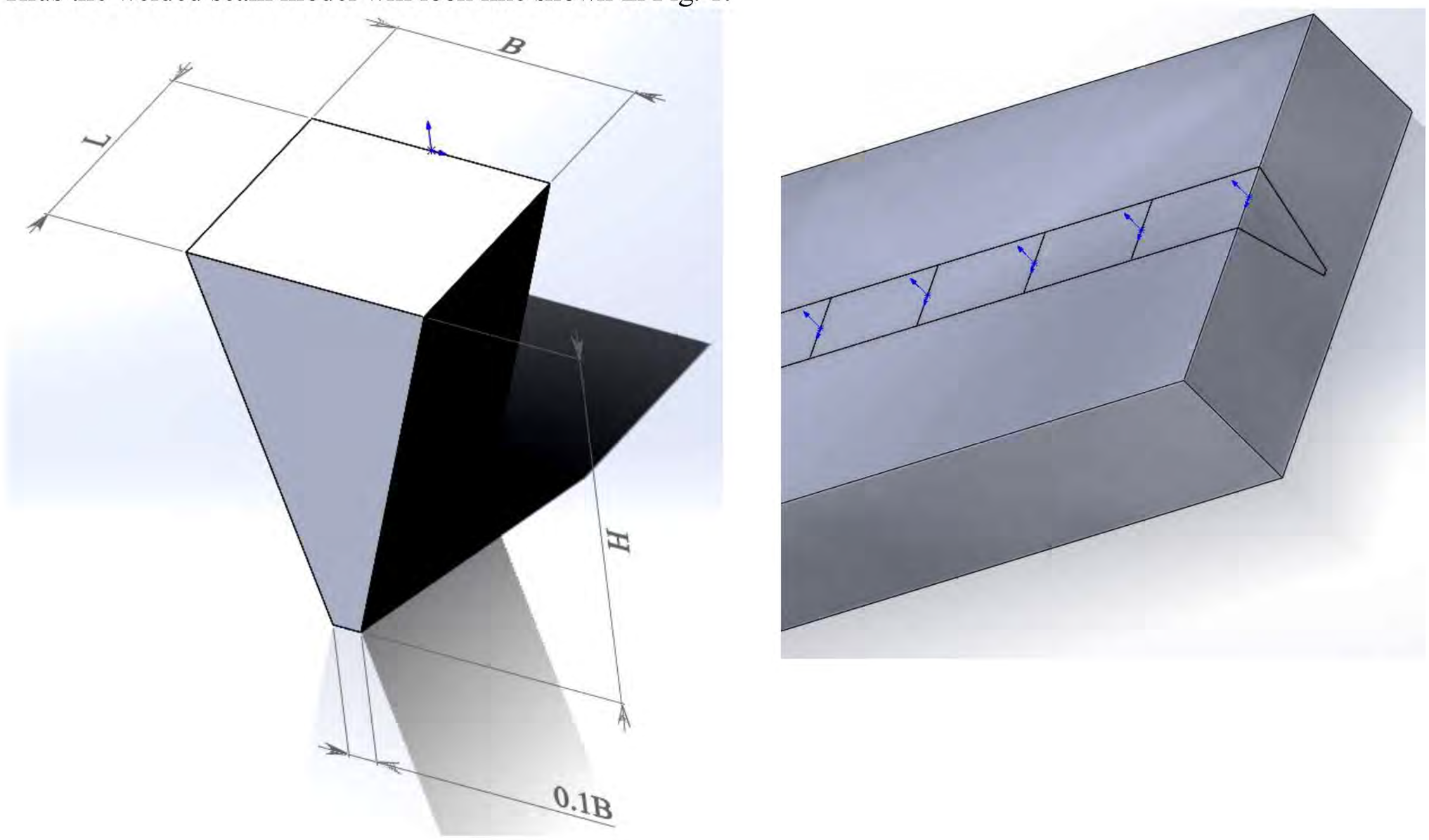

Fig. 1 3D welded seam model for incompletely fused welded samples

To verify the proposed technique of modeling the heat state of parts welded by laser bonding, numerical and test investigations were performed related to the temperature profiling of parts during welding and modeling their thermal state.

RESULTS

The process considered was the socket welding of steel 3 plates of 1.5 mm in thickness on an LKR-S robotic laser center of a Fanuc M710iC-50 six-axis robot, an IPG FLW D50 welding head, and an LS-5 5 kW ytterbium fiber laser. The welding mode was determined on the basis of the proposed dependences for calculating the melt pool parameters and ensured durable jointing at the incompletely fused jointing area. The test check of the welding mode at P=1 kW and ν=0.02 mps and zero setting of the laser's focal plane revealed the high efficiency of the proposed techniques.During the welding the temperature of the samples was measured using chromelalumel thermocouples and recorded using a digital multichannel recorder that ensured continuous multichannel recording on the computer HDD and synchronized visualization of the ongoing test processes on the monitor. The frequency of surveying each channel during the temperature recording was 100 Hz.For the layout of the thermocouples and the 3D welded seam model see Fig. 2.

In these conditions the effective efficiency factor of laser bonding is η_H =0,6 [11]. The metal melting temperature is T_L = 1535 ^{0}C,the in-liquid metal heat conductivity isλ_f= 40 W/m*K, the specific in-liquid metal heat capacity isc_f= 825 J/kg*K, the in-liquid metal density isρ_f = 7050 kg/m^3, the solid metal heat conductivity at the crystallization temperature is λ= 25 W/m*K [15, 16]. The melt pool's geometric characteristics at these parameters are: the length is L=1.5mm, the welded-through area width is$B$ = 1.7mm, the fusion penetration depth is$H$ = 2.6 mm.Thus a seam of 30 mm in length had 20 sections. The time it took the beam to pass each section was found as $\tau = L/\nu$ and amounted toτ = 0.08 seconds.

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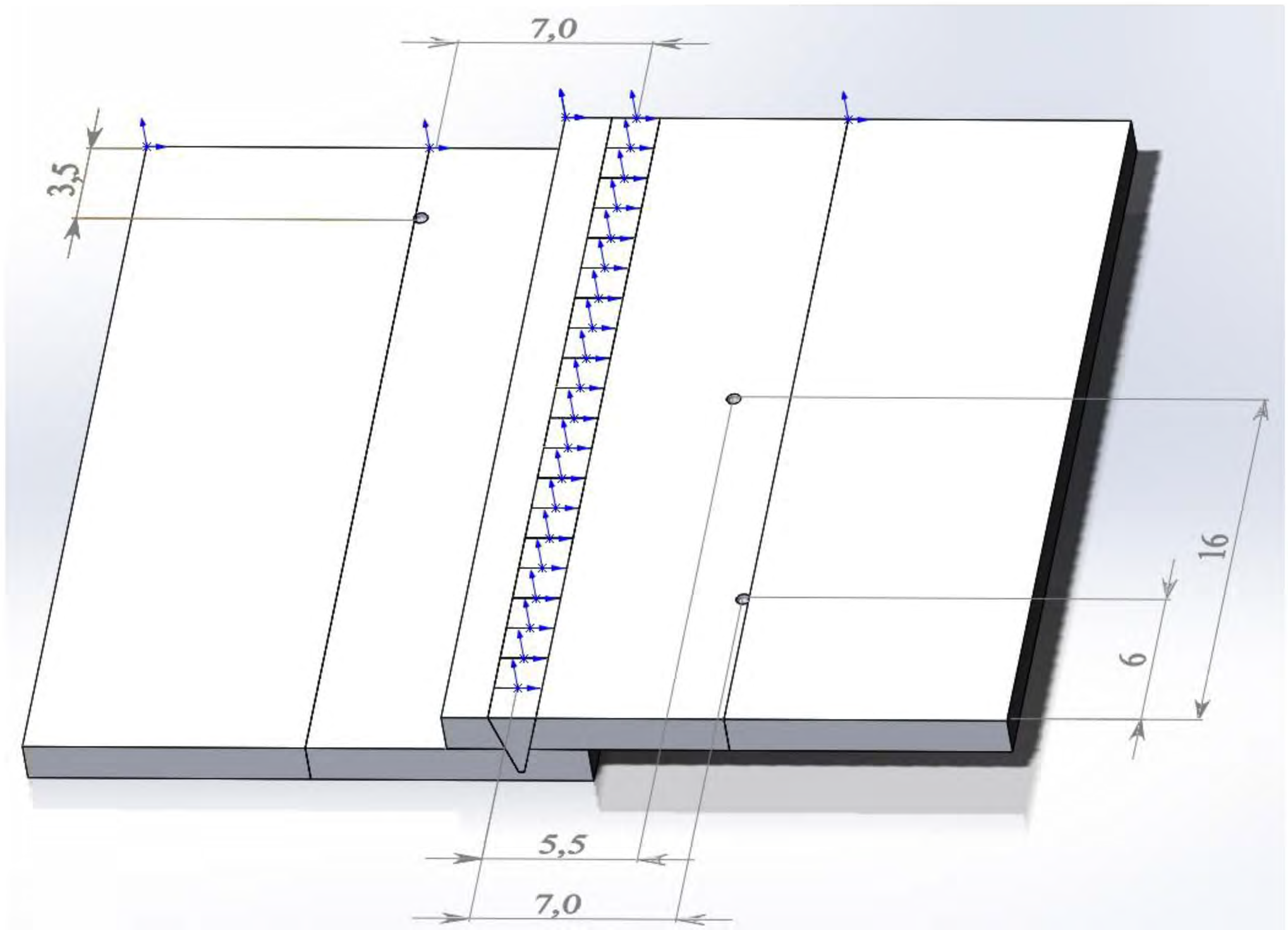

Fig. 2. 3D overlapping weld joint model with the layout of thermocouples

The non-stationary heat conductivity task was solved for each section in succession. The solution involved splitting the interval of passing each section in 50 time steps; the thermal field found in the last step was the initial conditions for the subsequent time interval. The withdrawal of heat from the surfaces of the welded samples was modeled using third-order boundary conditions (the heat emission factor was 200 W/m^2*K; the ambient temperature was 27 ^0C) that corresponded to the conditions of the welding area's blowoff with noble gas. The thermal physical properties of steel such as heat capacity and conductivity were set as functions of temperature.

The finite-element model consisted of 269293 nodes and 1444435 four-node volumetric elements with the average element rib size of 0.2 mm. The 3D models were designed in the CAD environment of the Solid Works suite. The calculations were performed in CAE – the SolidWorks Simulation suite. For the passage of heat in the plates during the welding see Fig. 3; for the thermal field at the onset of the cooling phase see Fig. 4.

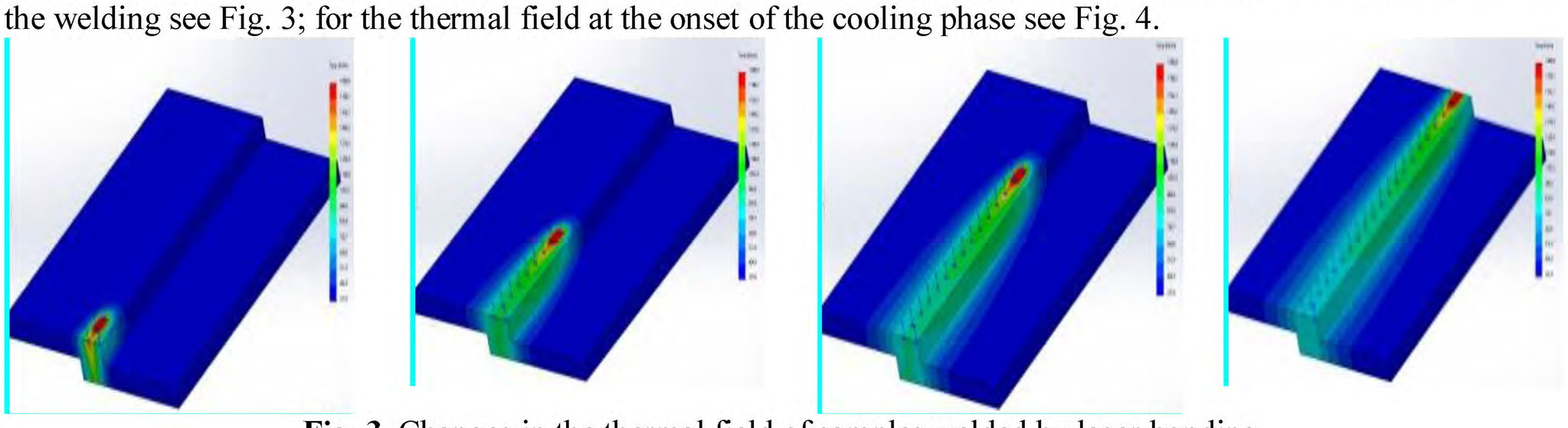

Fig. 3. Changes in the thermal field of samples welded by laser bonding

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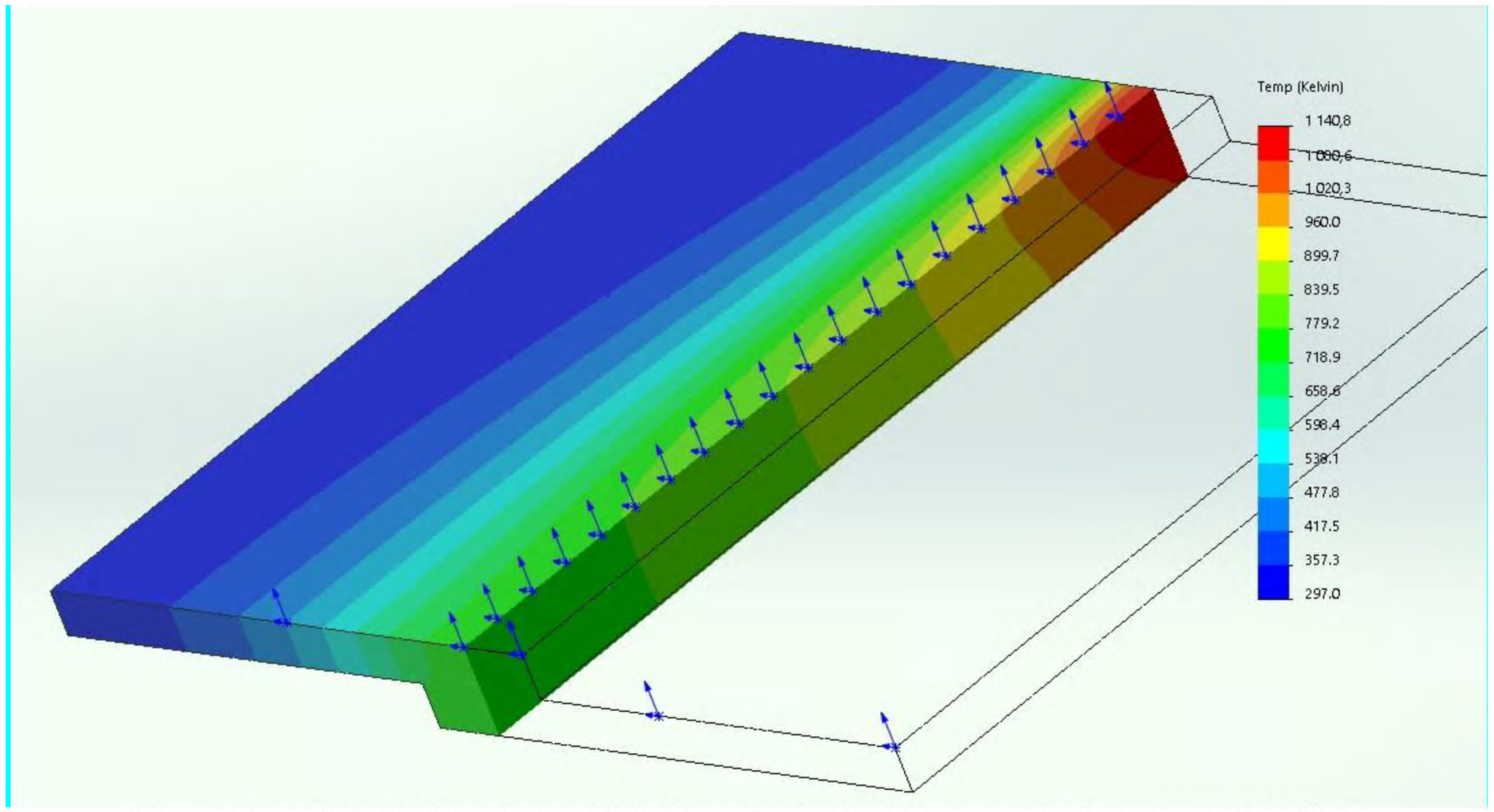
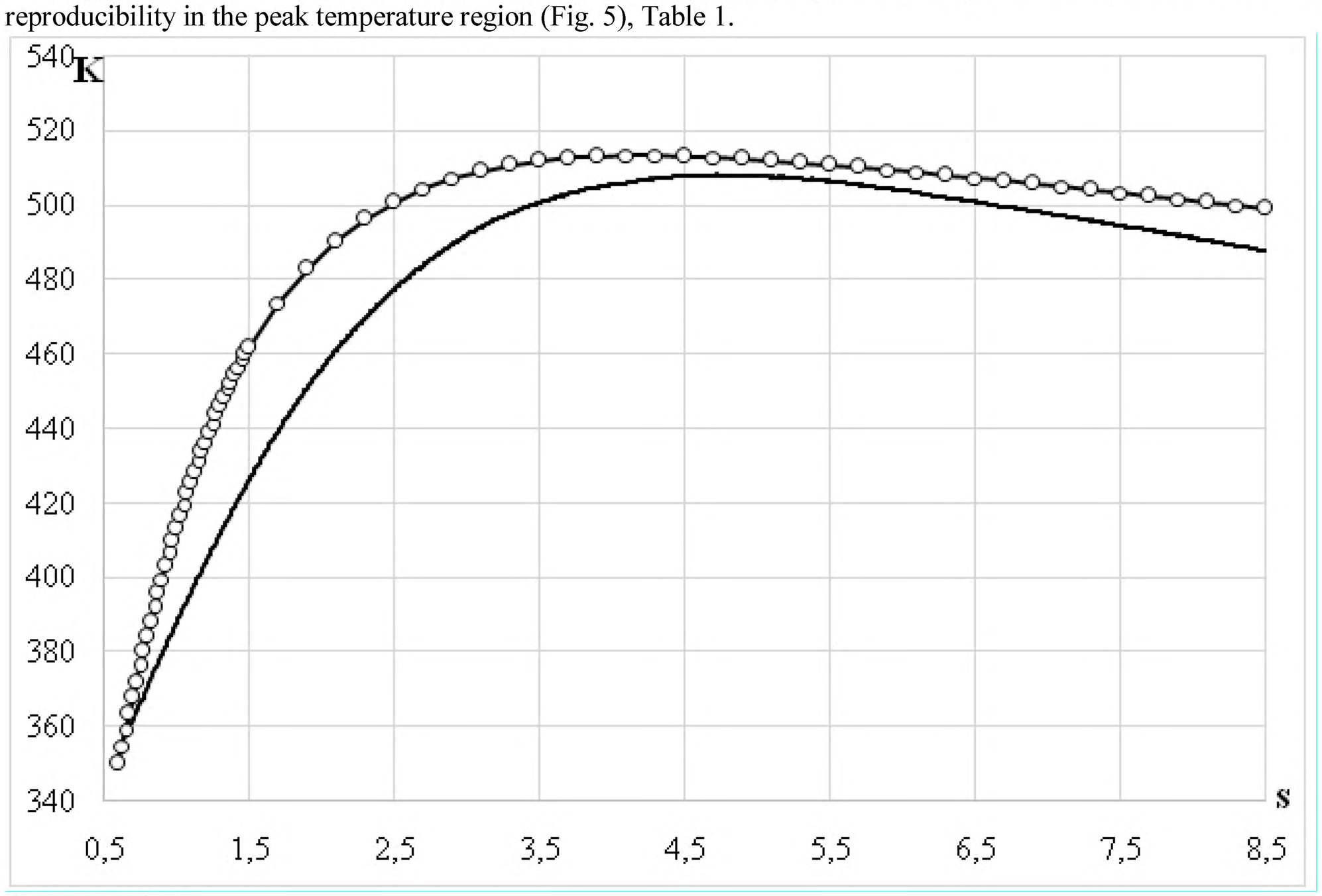


Fig. 4. Thermal field of overlap-welded plates of 1.5 m in thickness at the 0.4 second of cooling

The temperature in the thermocouple installation zones reaches the peak values in the cooling phase when the welding process is finished. According to the analytical comparison, the modeling and the test results show high reproducibility in the peak temperature region (Fig. 5), Table 1.



thermocouple 1

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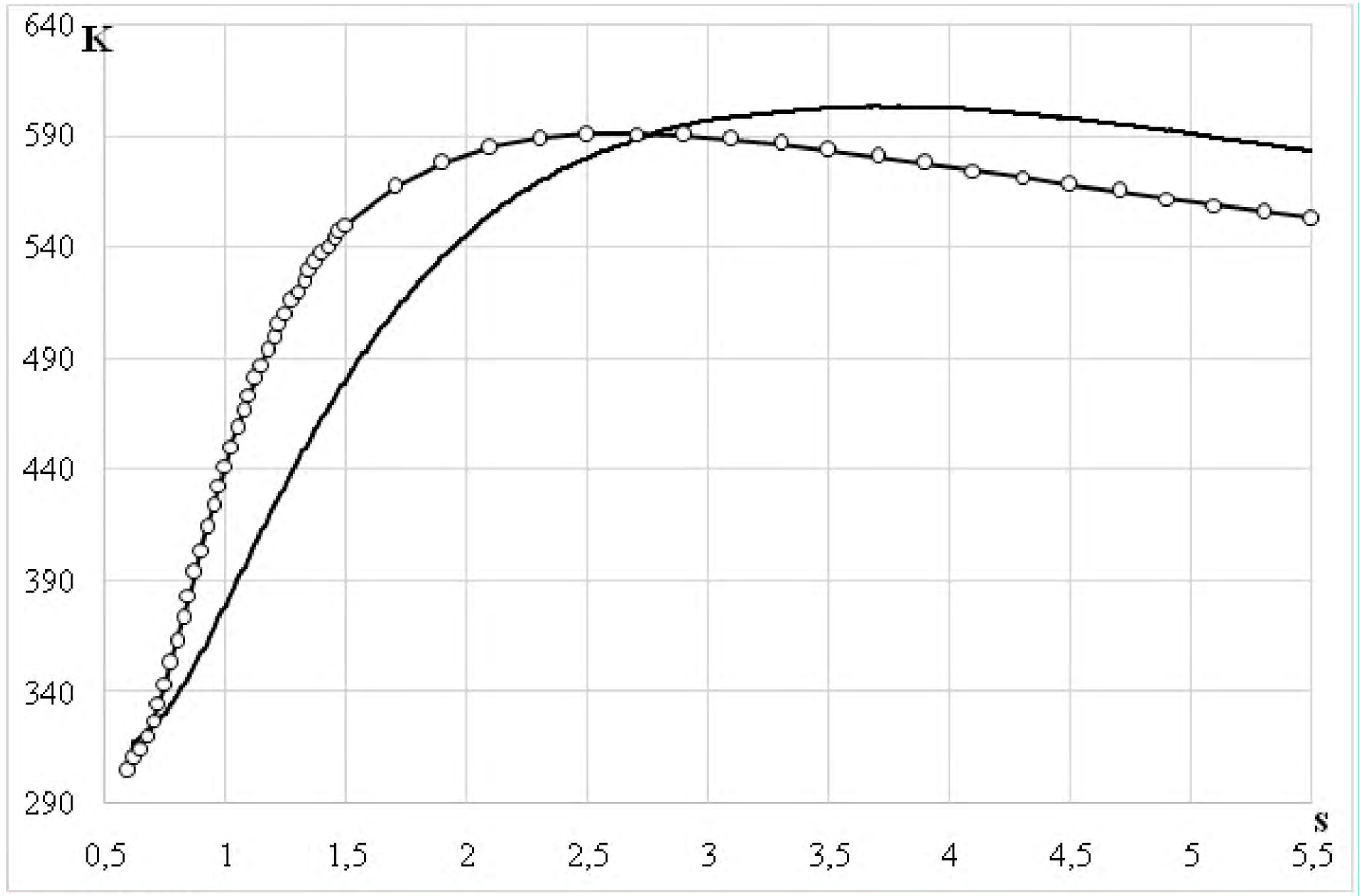
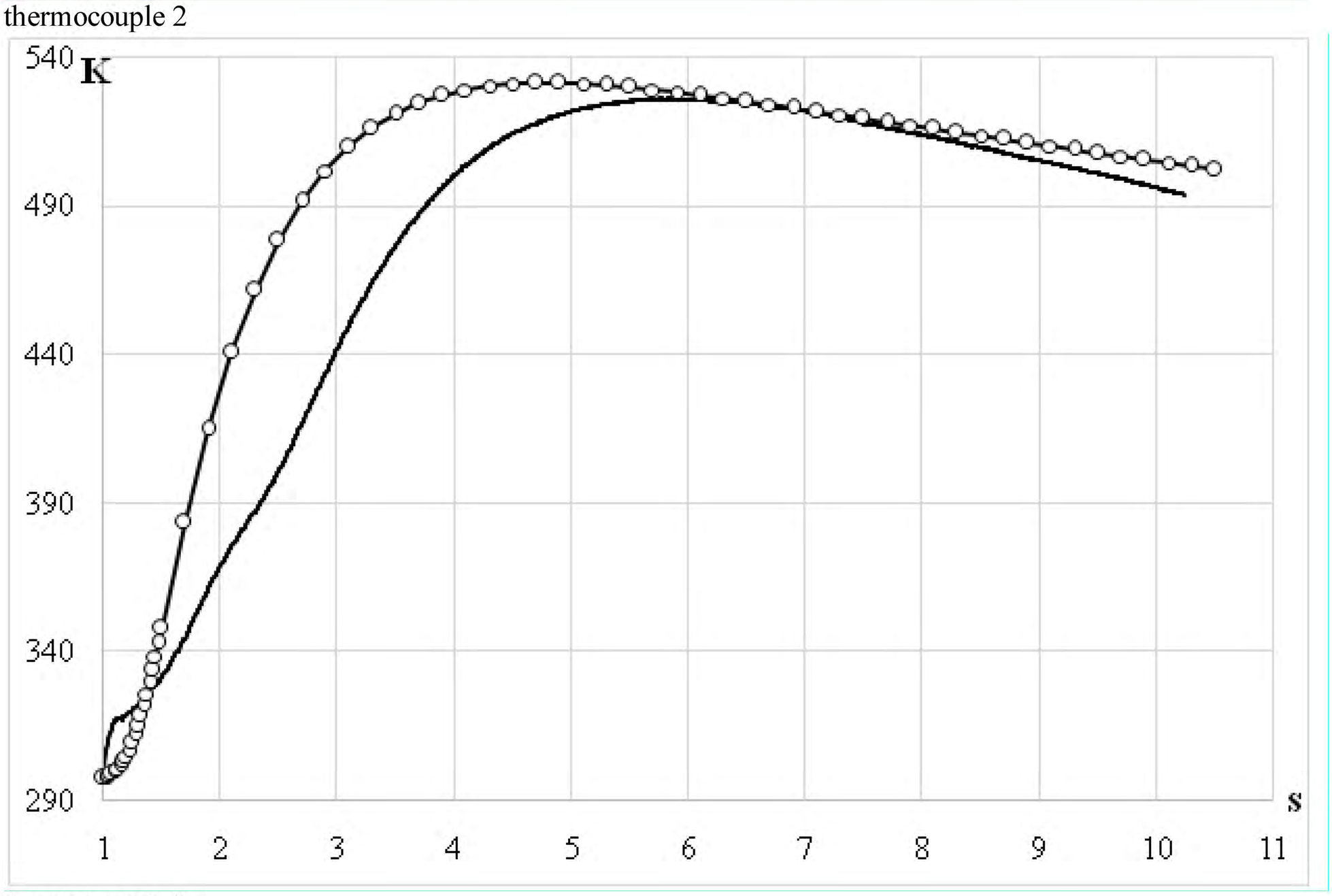


thermocouple 2



thermocouple 3

Fig.5. Design and experimental curves of temperature variations in reference points: —○— is the design curve, —— is the experimental curve

Table 1. Analysis of the results of modeling the laser bonding process and its experimental investigation

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Thermocouple no.	Tmax, K - experimental	Tmax, K - design	Relative difference, %
1	505	513	1.6
2	603	591	2
3	522	531	1.7

Some works, including those of the Khristianovich Institute of Theoretical and Applied Mechanics SB RAS [12, 13, 14] propose the 3D laser bonding model, where the flow of liquid metal in the melt pool is modeled using Navier-Stokes equations to describe the transfer of heat. The model takes account of phase metal transmutations, presence of a steam gas passage in the laser beam action zone, and its influence on the liquid metal convection in the melt pool. The given technique allows calculating the distribution of temperature in the melt pool, its boundaries, weld seam shape, and changes in the thermal field in the thermal action area during welding.The numerical and experimental investigation results published in [12, 13, 14] made it possible to evaluate the efficiency of the proposed technique of modeling the heat state of the welded samples by analytical comparison. For that purpose, the transfer of heat during the welding of steel 20 plates of 4 and 15 mm in thickness was modeled.

Now let us consider the welding of steel 20 plates of 4 mm in thickness with the 2.3 kW laser unit at a bonding speed ν = 2 m/min and the neutral position of the laser unit's focal plane [12]. The dimensional characteristics found at these parameters are: the melt pool length is L = 3.6 mm, the welded-through area width is B = 2 mm, the fusion penetration depth is H = 3.1 mm. The calculated dimensions are close to the melt pool parameters from [12] (L = 3.9 mm, B = 1.6 mm, H = 3.5 mm). The weld joint length in the model was 18 mm; i.e., the seam was divided in five sections on account of the melt pool length. The time it took the beam to pass each section was τ = 0.1074 s. The melt pool dimensions obtained during the welding of steel 20 plates of 15 mm in thickness with the 5.2 kW laser unit at a bonding speed ν = 0.01 m/min and the neutral position of the laser unit's focal plane [12] are: the melt pool length is L = 8 mm, the welded-through area width is B = 5 mm, the fusion penetration depth is H = 8.3 mm. The calculated dimensions are close to the melt pool parameters from [12] (L = 8.7 mm, B = 4 mm, H = 8.1 mm). The weld joint length in the model was 40 mm; i.e., the seam was divided in five sections on account of the melt pool length. The time it took the beam to pass each section was τ = 0.8 s. The task formulation and the FEM parameters were the same as in the modeling of overlap welding.

DISCUSSION

Now let us compare the results of modeling the thermal field of welded plates in the reference points with equal coordinates (Table 2). The coordinates start at the point, where the seam's symmetry axis that coincides with the 0X axis crosses the remote boundary of the melt pool (Fig. 6). The X0Z plane is the seam's symmetry plane. The reference points and the process duration were selected according to the modeling results given in [12]. The analytical comparison was made using the results from the third time interval (Fig. 6), i.e., 2.4 and 0.3222 seconds of the welding of plates of 15 and 4 mm in thickness, respectively.

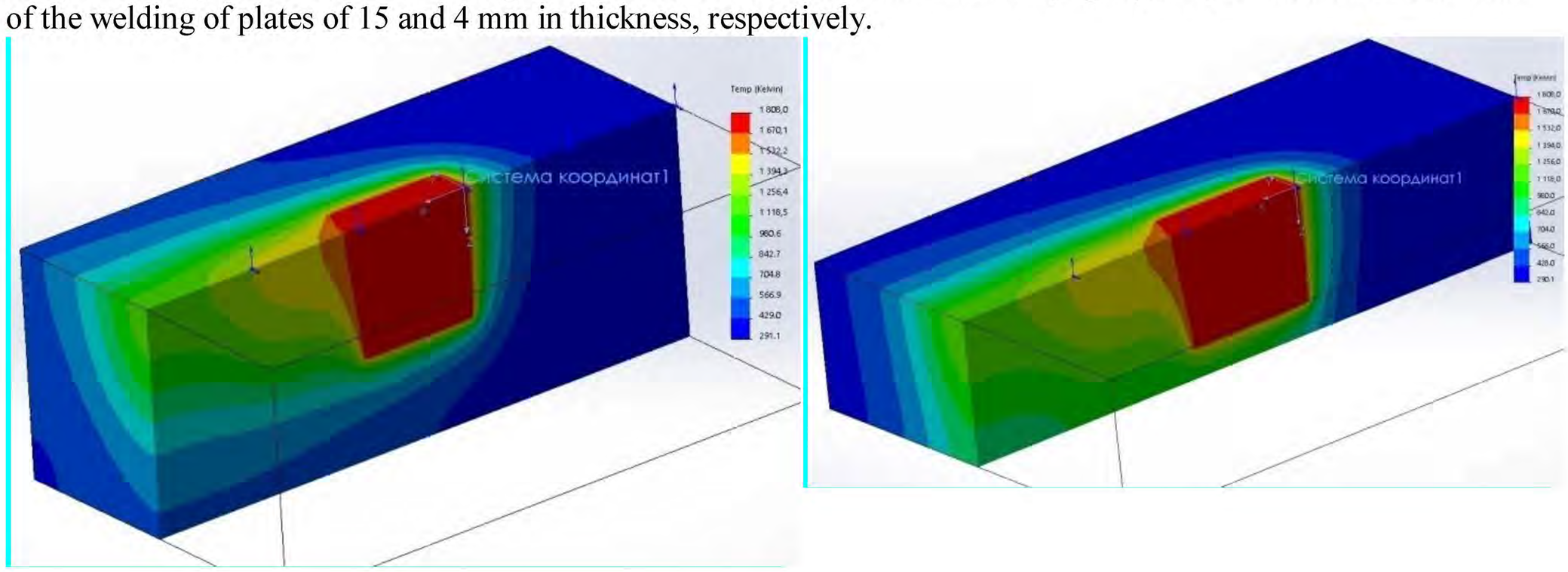

Fig. 6. Thermal field of the welded plates in the last step of the third interval of laser bonding

Table 2. Analytical accuracy comparison of laser bonding simulation

Results of modeling the welding of steel 20 plates of 15 mm in thickness			
Reference points	Temperature in the	Temperature in the	Relative difference in

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coordinates [6]: X, Y, Z (mm)	reference points acc. to the technique from [6]	reference points acc. to the proposed technique	results (%)
12,2; 0; 0	1400	1470	5.0
19; 0; 0	1100	1165	5.9
8; 3,4; 0	1100	1158	5.3
10; 0; 3	1400	1460	4.3
15; 0; 4	1100	1180	7.3
Results of modeling the welding of steel 20 plates of 4 mm in thickness			
6; 0; 0	1400	1450	3.6
9,6; 0; 0;	1100	1180	7.3
4; 1,2; 0	1100	1163	5.7
4,8; 0; 1.3	1400	1437	2.6
4,8; 0; 2.6	1100	1180	7.3

CONCLUSION

The results of modeling and experimentally investigating the heat transfer duringthe laser bonding of samples of uniform materials allow making the conclusions expounded below.

The proposed approach to modeling the thermal state of parts welded by laser bonding makes it possible to design to high precision (Table 1) the thermal field in thermal influence areas, which is confirmed by the results of in-welding thermal profiling. It is known that the residual stresses generated in the process of welding and the structural changes in thermal influence areas reduce the static and fatigue structural integrity. The precision of the numerical evaluation of residual stress levels and their influence on the structural integrity depends on the precision of defining the thermal field in thermal influence areas.

The proposed technique makes it possible to ensure precision required in engineering design and can be implemented as part of solving the non-stationary heat conductivity task by the finite elements technique in modern CAE suites.

The techniques of modeling heat exchange during laser bonding that are proposed by some researchers rely on modeling the flow of liquid metal in the melt pool and evaporation of metal in the steam gas passage.Such models are highly precise and make it possible to find the distribution of temperature and metal phase boundaries in the melt pool and define its shape; however, they are embodied in original program suites and require massive computational resources. The proposed technique does not consider the processes in the melt pool but allows calculating the dimensional parameters of the weld seam cross section and the melt pool length that determines the seam's discreteness in the model and the time of heat supply in each of the sections. The temperature at the melt pool boundary is equal to the metal melting temperature; thus the modeling process consists in solving the non-stationary heat conductivity task with first-order boundary conditions in the heat supply areas.According to the analytical comparison of the modeling results (Table 2), there are minor temperature differences among the reference points for the thermal influence area.

The proposed technique allows modeling the thermal state of welded parts using modern CAE suites not on the samples but on the full-size finite element model of the test assembly, which allows arranging the solution of conjugate tasks in one finite element model.

RECOMMENDATIONS

The proposed technique makes it possible to ensure precision required in engineering design and can be implemented as part of solving the non-stationary heat conductivity task by the finite elements technique using modern CAE suites. The ultimate result of using the implemented technique is the possibility to model the thermal state of welded parts using modern CAE suites not on the samples but on the full-size finite element model of the test assembly, which allows arranging the solution of conjugate tasks in one finite element model. According to the calculated changes in the thermal field upon the welding of steel plates together by laser bonding, the proposed model adequately describes the transfer of heat in the welding region. The attained results can be recommended for the product design and production engineering in mastering new small-size fine-mechanics products with high requirements on reliability in further operation[3, 4].

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