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Pavlo Anikin

RESEARCH OF THE INFLUENCE OF THE USE OF A FEEDBACK TELECOMMUNICATION SYSTEM ON THE WIRE ARC ADDITIVE MANUFACTURING PROCESS

The object of the research is the possibilities of using a wireless communication system for feedback to improve the additive manufacturing process of a part using the arc welding technology with temperature control for heat propagation.

The problem to be addressed includes determining the geometric properties, print topology, and temperature control regimes for the mentioned part. It also involves the installation of telecommunications sensors and cameras for temperature monitoring, conducting simulation calculations using ABAQUS software, and physical experiments.

The results of the work include simulating the additive manufacturing process at necessary hierarchical system levels, considering specific requirements and obtaining the required geometric dimensions. Residual stresses have been analyzed, software-related heat propagation issues have been discussed, the influence of cooling on production quality has been verified, and optimal print parameters have been created. Additionally, the potential use of a feedback telecommunication system with telecommunication devices such as cameras and laser sensors for temperature control has been explored. The obtained data has been used for the possibility of generating an automated program for robot control during the additive manufacturing process. Based on the data obtained, residual stress values and defects in the produced samples were determined. A real experiment was conducted, and the results of the real experiment were compared and analyzed.

The assessment of the impact of the feedback telecommunication system on the additive manufacturing process using arc welding with heat propagation control through cooling periods in practice allows for improved printing quality, technology of the produced part, cost reduction, and speeding up the production process.

Keywords: *WAAM, electric arc welding, CAE systems, robotics, 3D modelling, Abaqus, wireless telecommunication feedback system.*

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1. Introduction

The use of additive manufacturing with arc welding still raises many questions about the possibility of improvement and automation of the process. Utilizing feedback systems to control temperature regimes using wireless devices significantly broadens the scope of methods to enhance the printing process, ultimately providing options for better control over residual stress distribution and the method of manufacturing parts. This, in turn, accelerates the printing process and reduces the risk of defects. One of the key advantages of using telecommunication systems is the ability to collect and transmit data in real-time. Temperature sensors can be directly installed on robotic equipment (Fig. 1), where they continuously measure the temperature during the process. These data are transmitted to the control system via a wireless communication channel. These innovative approaches make additive manufacturing more appealing to various industrial sectors as they enhance productivity, quality, and manufacturing reliability. The development of these technologies creates opportunities for new applications and the expansion of industries where additive manufacturing can find its place and become a key method of production in the future.

Fig. 1. Robotic WAAM system at Triada LTD Co.

Previous research on improving the additive manufacturing process using arc welding technology [1–4], including automation [5], and the use of temperature control systems [6] has indicated that robotic systems still have unresolved issues. Additionally, simplifying robot operation and creating necessary software for expanding usage remain important concerns. Modern temperature control methods [7–9] require improvement and the possibility of integrating real-time telecommunications feedback systems [10], such as thermal cameras and thermal laser sensors, to address issues related to heat distribution among layers and methods of their overlap [11–15].

Therefore, *the object of this research* is the possibilities of using a wireless communication feedback system to improve the additive manufacturing process of a part using arc welding technology with temperature control for heat propagation. *The aim of this paper* is to select the necessary levels of a three-tier hierarchical model to conduct preliminary simulations for addressing the issue of temperature control during the printing process and to conduct further real experiments. To achieve the set goal, the following tasks need to be addressed:

- establish geometric parameters and select the material;
- simulate the necessary levels of the hierarchical model;
- find solutions if there are issues with temperature control during the simulation;
- conduct practical experiments using the feedback telecommunication system;
- verify the theoretical and practical feasibility of solving the temperature-related challenges;
- analyze the obtained data and draw conclusions regarding the printing process and the potential use of the feedback telecommunication system for improvement and further automation of the manufacturing process.

2. Materials and Methods

Uncontrolled heat impact can not only result in a deterioration of the quality of the produced part but may also lead to its complete destruction. To achieve proper temperature control, it is possible to use preliminary simulations and optimize the robotic arm's motion trajectory during the additive manufacturing process [16]. Computer computational programs for modeling the thermal regime of printing using arc welding can employ heat propagation equations based on the Goldak model. These equations allow for the analysis and prediction of temperature distribution during the additive manufacturing process, assisting in maintaining proper control over the thermal influence on the manufactured parts [17, 18]:

$$q_{f/r}=\frac{6\sqrt{3}f_{f/r}Q}{abc\pi\sqrt{\pi}}e^{\left(-\frac{3x^2}{c_{f/r}^2}\right)}e^{\left(-\frac{3y^2}{a^2}\right)}e^{\left(-\frac{3z^2}{b^2}\right)}. \tag{1}$$

The equation $Q=nVI$ describes how energy is distributed within a system and depends on the values of current (I), voltage (V), and efficiency coefficient (n). The sizes of heat propagation in the system take on an ellipsoidal form, and their magnitudes are denoted as a, b, and c.

There are partial factors that affect the amount of heat in the system, and one of them is f_f, which accounts for the front part of the system, and the other is f_r, which accounts for the rear part of the model. It's important to note that the sum of these two partial factors, i. e., f_r+f_f, equals 2.

Using a three-tier hierarchical model [19] for simulating the additive manufacturing process with arc welding provides the capability to verify the feasibility of the printing process before its commencement in real life. This enables an examination of heat propagation and its influence on residual stresses, helping to determine the optimal conditions for the arc welding printing process. By analyzing these results, researchers can identify the most effective parameters and optimization methods that contribute to improving the printing process and enhancing the quality of the manufactured products.

3. Results and Discussion

To accomplish the task of improving the additive manufacturing process using arc welding, it is necessary to simulate the chosen scenario. The selected material development option involves creating a single-layer geometric shape with a bead width of 4 mm. Since the project comprises only one layer, the simulation of the three-tier hierarchical model will use only two simulation levels: the bead and the layer. An evaluation of simulation data for temperature regimes and residual stresses will be conducted.

For the printing simulation process, aluminum has been selected as the material. The material parameters are provided in Tables 1, 2.

The process of computer calculations follows a predefined algorithm for conducting simulations at the levels of the three-tier hierarchical system. After the simulation is completed, the necessary components will be selected, the use of a feedback system to enhance the process will be verified, and the part will be printed directly.

Table 1

WAAM aluminum properties

Conductivity		Density	Elastic			Expansion		Inelastic Heat Fraction
T, °C	q, W/m·°C	ρ, kg/m^3	T, °C	σ, N/m^2	v	T, °C	ε, °C	c, °C
300	164	2750	25	724e9	0.3	300	27e-006	900
500	194		500	63.5e9		500	27.4e-006	
700	210		700	56.1e9		700	27.7e-006	
770	220		770	50e9		770	28.3e-006	

Table 2

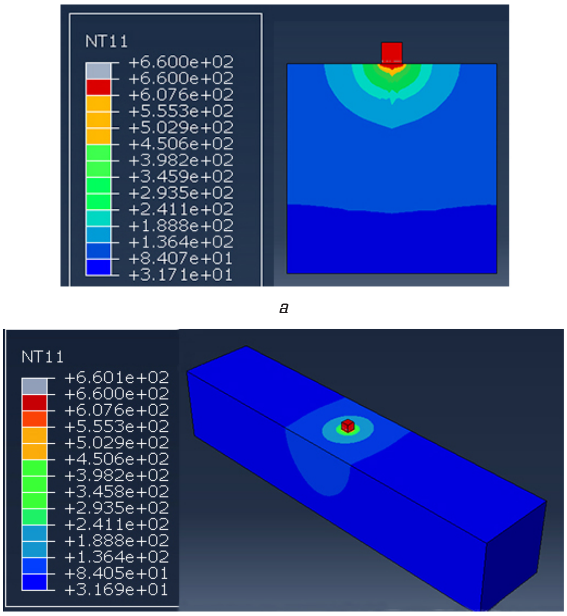
Additional WAAM aluminum properties

Conductivity	Density	Elastic		Expansion
q, W/m·°C	ρ	σ, N/m^2	v	ε, °C
204	2750	69e9	0.33	2.3e-005

For simulating the first level, the results of previous research on calculations at the first level of the three-tier hierarchical model of the additive manufacturing process using arc welding [19] are utilized.

From the analysis of the results of temperature regimes and heat propagation at the first level (Fig. 2), it is evident that the temperature propagates normally, in accordance with the planned results. This is a positive signal indicating the adherence to technological parameters and the quality of the object's preparation for welding.

The results of the structural analysis at the first level of the three-tier hierarchical model, based on the thermal analysis, provide information regarding the distribution of residual stresses (Fig. 3), which directly affect the possibility of deformations occurring during the cooling process and becoming the cause of defects such as cracks or deformations.



a

b

Fig. 2. Results of thermal analysis and heat propagation at the first level of the three-tier hierarchical WAAM model: *a* – overall view; *b* – cross-sectional view

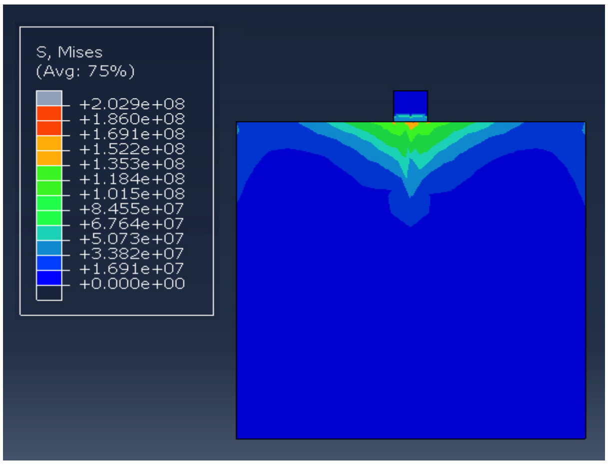


Fig. 3. Results of structural analysis and residual stresses at the first level of the three-tier hierarchical WAAM model

Analyzing the results obtained at the first level of the three-tier hierarchical simulation model of the project, it can be concluded that no deficiencies were identified. The temperature propagates normally, and the presence of residual stresses is satisfactory.

Based on the results and data analysis at the first level, it is necessary to conduct the simulation of the second level of the three-tier hierarchical model of additive manufacturing using arc welding – the layer. The required geometric structure of the layer will consist of 5 bead passes (Fig. 4). During the simulation, the beads will be applied one after another to the base material.

First, a temperature analysis needs to be performed. To conduct the temperature analysis and check the heat propagation, temperature data will be collected at the marked points denoted by red dots on the created geometric model (Fig. 5). This will allow to compare the heating results of the system during issue occurrences and the use of various options for addressing them.

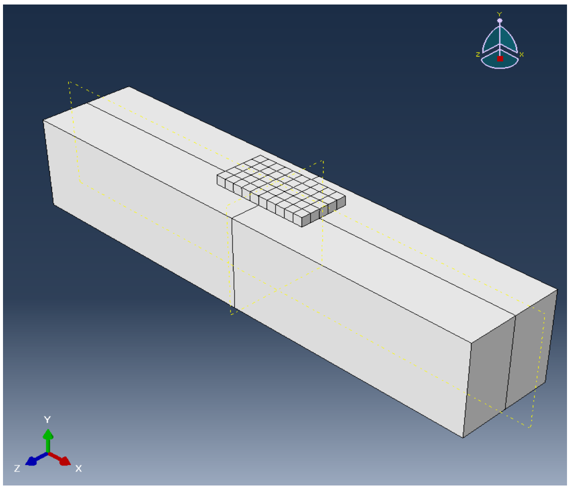


Fig. 4. Simulation project for the second level of the three-tier hierarchical WAAM model

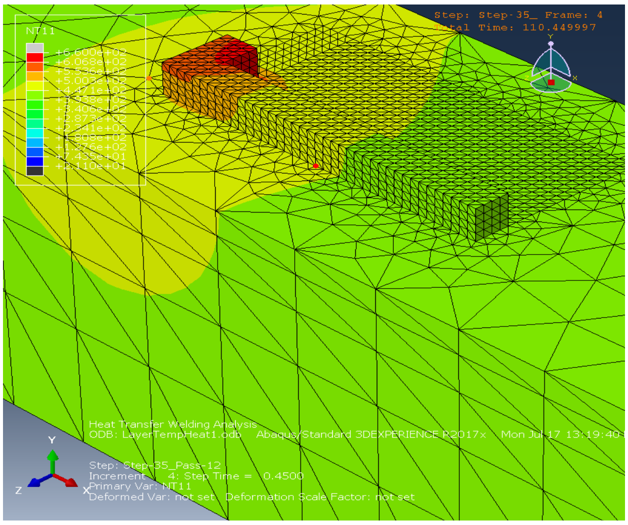


Fig. 5. Temperature measurement point during the simulation of the second level of the three-tier hierarchical WAAM model

One of the initial challenges that arises during the development of the layer project is the bead deposition trajectory. The chosen bead deposition topology (Fig. 6), allows for better control of heat propagation during the additive manufacturing process.

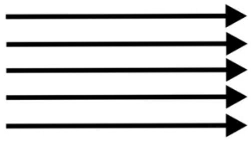


Fig. 6. Bead deposition trajectory in the layer

During the temperature analysis simulation process (Fig. 7), the temperature begins to reach critical values as early as at the 16th deposition step. Without stopping the system, without cooling, and continuing material deposition, the cumulative heat accumulation reaches critical values at the 22nd deposition step. The system experiences a failure. The additive manufacturing simulation process fails.

The simulation revealed that the current welding process parameters are not effective enough to avoid temperature overload of the system. To address this issue and prevent similar failures, it is necessary to implement a cooling system after every *n* number of steps. This will help reduce the temperature accumulation in the system for successful completion of the printing process. In the current scenario, forced cooling to 60 °C was selected after every 20 rolls, which means two passes along the trajectory of roll application during layer creation. During a real experiment, such a method can be implemented using a telecommunications feedback system with the use of thermal cameras and/or thermal laser sensors, allowing for process control and automation.

The simulation process with cooling after every 20 passes provides information about the partial success of such printing (Fig. 8). At times, the system reaches critical values, leading to partial failure. It is possible to see that during steps 16 and 36 of the collocation, heat accumulation is already excessive. Because forced cooling occurs at steps 20 and 40, the system avoids complete destruction. However, this additive manufacturing method can still create print defects and is not optimal for use.

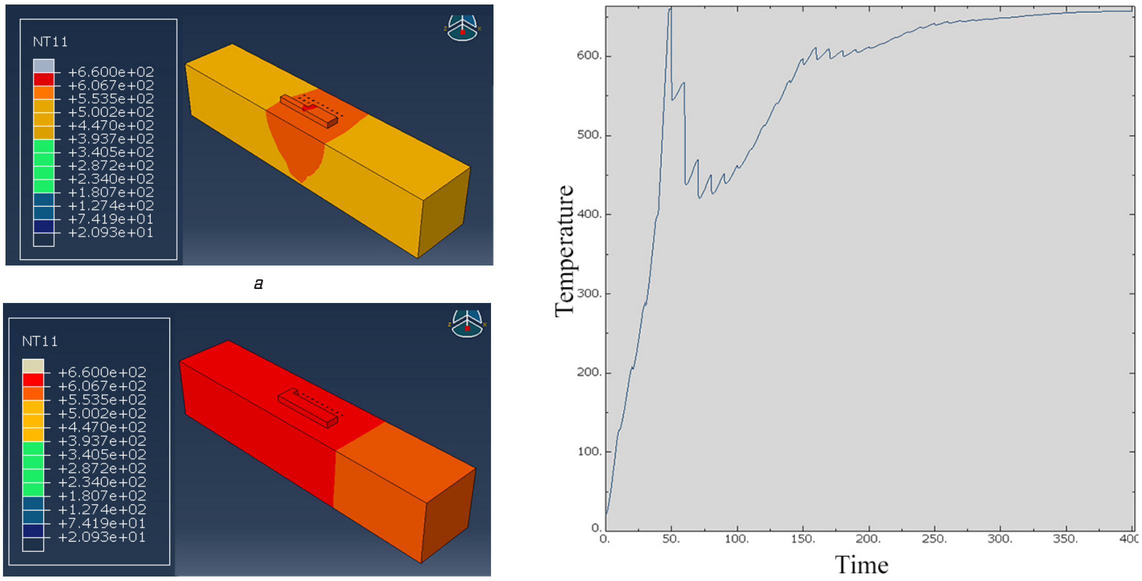
To address the current problem, there was a need for more frequent cooling. The previous cooling method after every 20 passes or every two passes in the length of applying a part of the layer was found to be insufficient. A new testing method was chosen – forced cooling to 60 °C after every 10 passes or after every pass in the length of applying a part of the layer.

Similar to the previous method, this approach can be implemented during a real experiment using a telecommunications feedback system with a thermal camera and/or thermal laser sensors.

The analysis of the results of the thermal simulations of the second level of the three-level hierarchical model of additive manufacturing using arc welding with more frequent cooling reveals that there is normal heat distribution during all deposition steps, the temperature does not reach a critical level, and the printing simulation proceeds normally (Fig. 9).

Based on the obtained results of the temperature simulation, it is possible to perform a structural analysis simulation. Comparing the results of the simulation in which cooling occurs every 20 passes (Fig. 10, *a*) with the simulation in which cooling happens every 10 passes (Fig. 10, *b*), it can be observed that temperature distribution and heat accumulation parameters affect residual stresses. In the first case, during loads, peak values occur precisely where the readings reached critical temperatures. In the second case, the distribution of residual stresses is more uniform, as reflected in the graph (Fig. 10, *b*), and contributes to the greater strength of the manufactured part.

Using the obtained data, it is possible to proceed to conducting a real experiment. For the real experiment, a robotic welding system provided by «Triada LTD Co» (Zaporizhzhia, Ukraine) will be used. The material used is aluminum. The initial temperature is 25 °C. The melting and collocation temperature is 660 °C. To ensure a successful manufacturing process, a telecommunication feedback system will be used to control the temperature regime, involving the collection of information from a thermal camera and laser sensors. Both data-collecting devices are connected to a data transmitter, which wirelessly transmits information to a receiver connected to a controller and automation program. In case of deviation from the regime, excessive heat accumulation, or according to the programmed plan, the system will be stopped.

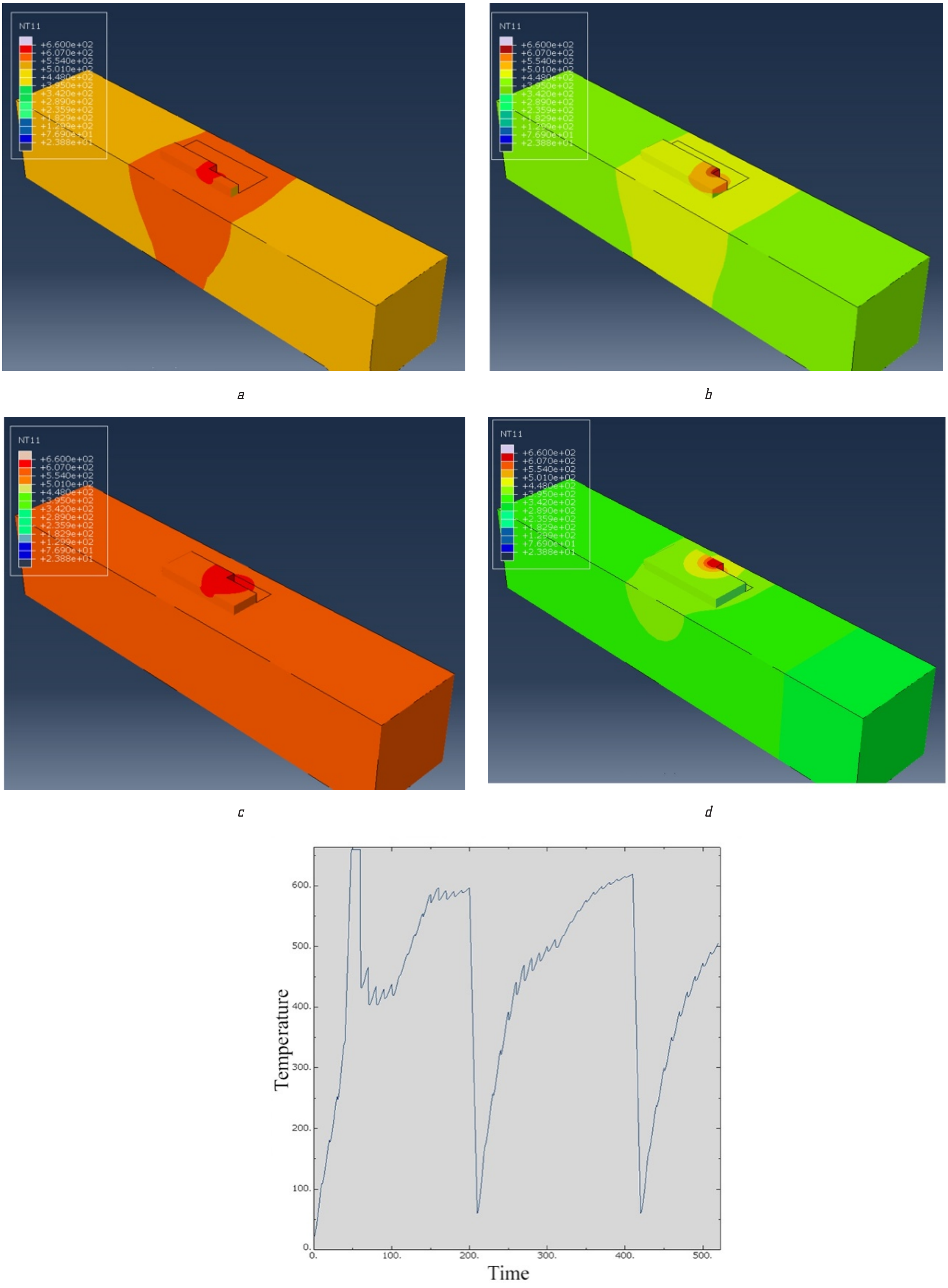


a

b

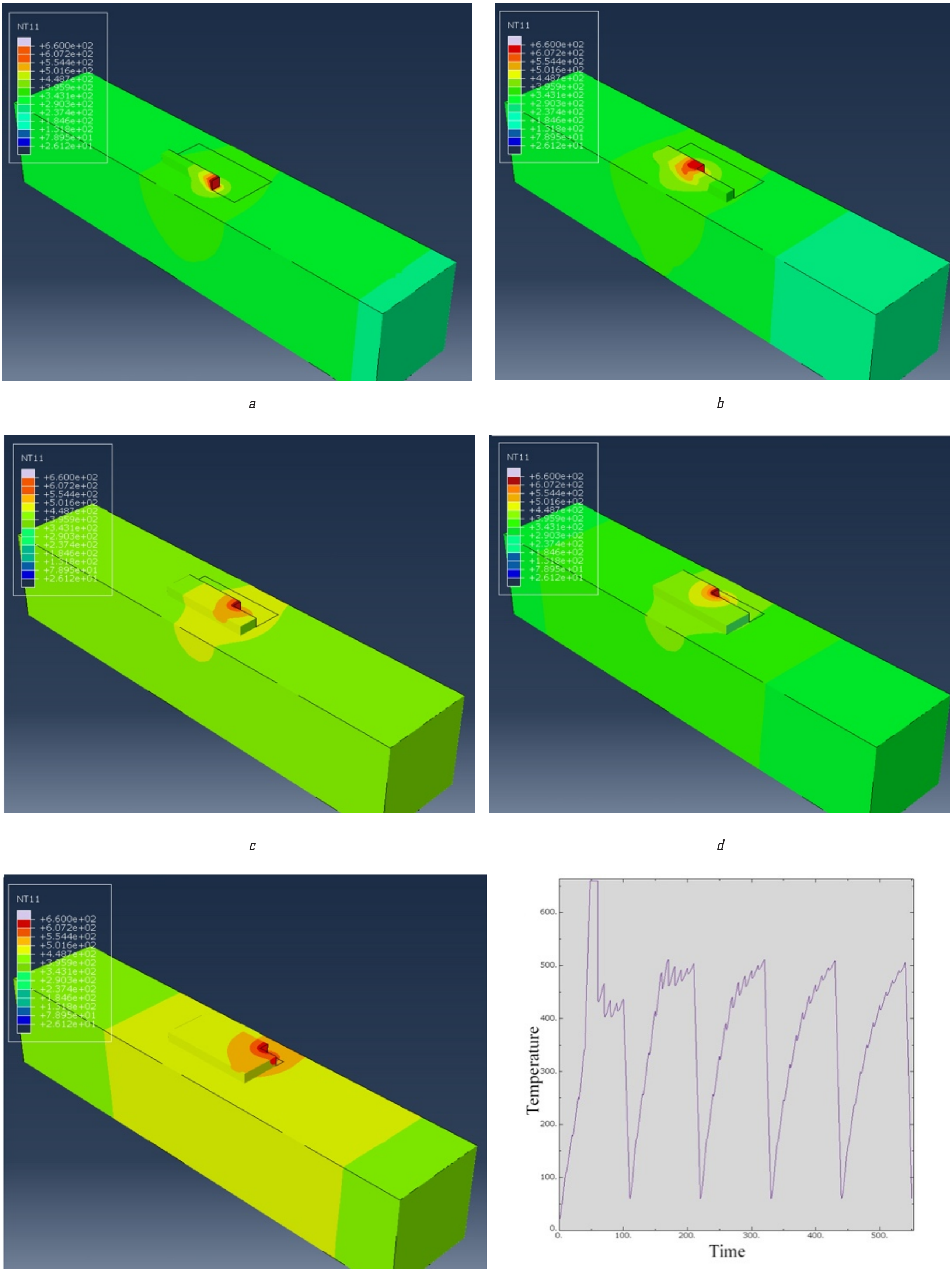
c

Fig. 7. The results of the thermal analysis and heat distribution of the second level of the hierarchical three-level WAAM model: *a* – step 16; *b* – step 22; *c* – temperature analysis



a *b* *c* *d* *e*

Fig. 8. Results of the thermal analysis and heat distribution of the second level of the hierarchical three-level WAAM model with cooling: *a* – step 16; *b* – step 32; *c* – step 20; *d* – step 40; *e* – temperature analysis

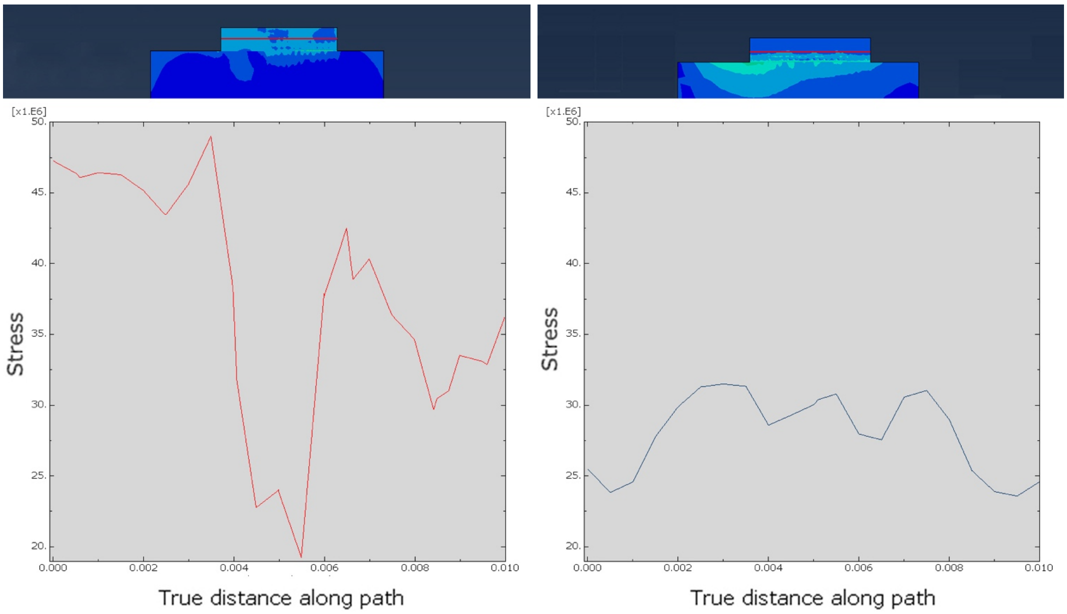


a *b*

c *d*

e *f*

Fig. 9. The results of the thermal analysis and heat distribution in the second level of the hierarchical three-level WAAM model with more frequent cooling: *a* – step 6; *b* – step 14; *c* – step 26; *d* – step 34; *e* – step 47; *f* – temperature analysis



a *b*

Fig. 10. Results of the structural analysis of the second level of the three-level hierarchical WAAM model: *a* – with regular cooling; *b* – with more frequent cooling

For the experiment, a Bosch GIS 1000 C Professional thermal camera (Germany) was chosen, with a temperature range from –40 °C to 1000 °C, as well as an infrared sensor with an operational range from –20 °C to 1200 °C. By monitoring the welding process (Fig. 11), the thermal infrared camera not only allows for controlling the printing according to the specified parameters but also provides data for further analysis and development. The result of the real experiment is two printed layers (Fig. 12).

On the layer with the number 1, defects and damage caused by excessive heat accumulation can be observed. This particular case was printed using cooling after every 2 passes. In comparison, the layer with the number 2 shows no defective formations and satisfies the parameters for technological production. This result was achieved by using cooling after each pass of printing.

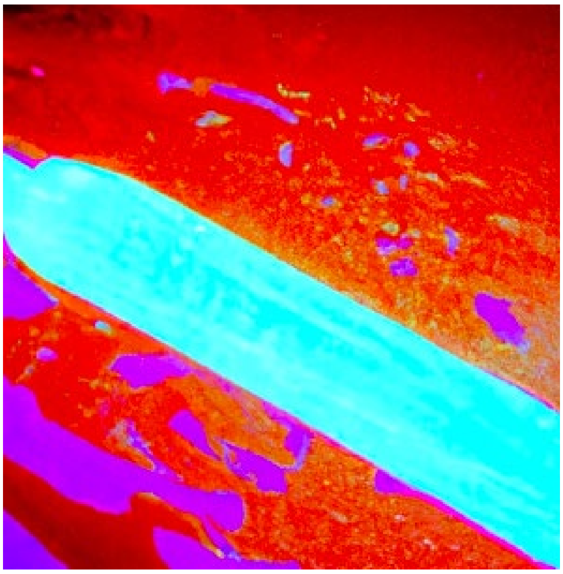
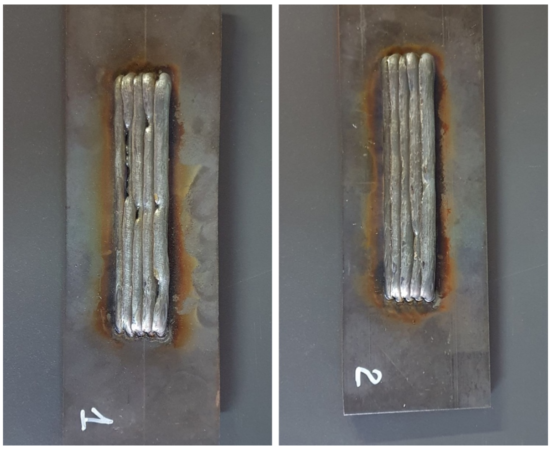


Fig. 11. Infrared photo of the additive manufacturing process using arc welding



a *b*

Fig. 12. The results of the additive manufacturing process using arc welding: *a* – the first case; *b* – the second case

The practical significance of the research lies in the potential use of feedback systems to improve and expedite the additive manufacturing process using arc welding. It also allows for the automation of temperature control during direct printing, reducing production costs and simplifying user interaction.

Research limitations include the manual input and calculation of cooling parameters and their subsequent impact on the additive manufacturing process using arc welding.

Additionally, the study was constrained by the limitations imposed by the wartime conditions, which hindered the ability to conduct experiments 24 hours a day due to curfews and frequent power outages from enemy attacks. The technologies studied have prospects for application in military production when creating metal products of small and large sizes.

Future research prospects involve further automation of the additive manufacturing process using arc welding and the proposed feedback system. While the automated calculation of robotic system control for simple geometric components is possible, it still requires significant human intervention for successful completion. For instance, the simulation process for simple geometric components could be automated by inputting only relative data for simple geometric figures. After the simulation is conducted and the necessary optimal parameters are obtained, this data could be automatically transferred to the controller to initiate the printing process. The feedback system would operate in real-time, transmitting data back to the simulation program and conducting simulations for subsequent stages for adjustment. There is a need to develop a centralized program for the automation of the process, integrating various stages of automation.

4. Conclusions

As a result of the conducted research, a positive influence of the telecommunication feedback system on the additive manufacturing process using arc welding has been established. The following key points have been identified:

1. Feedback resolves some of the issues related to temperature control during the printing process, including:
   - monitoring the heat distribution and accumulation;
   - monitoring for the presence of geometric defects.
2. Properly selected types of thermal cameras and sensors for system control through wireless communication expedite the printing process and improve print quality.
3. A system equipped with a telecommunication feedback system, unlike systems without it, reduces the number of defects and production costs, as proven by the conducted experiment.

The obtained data are essential for developing an automated program using thermal telecommunication sensors for the additive manufacturing process with arc welding.

Conflict of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The manuscript has associated data in a data repository

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

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Pavlo Anikin, *Postgraduate Student, Department of Radio Engineering and Telecommunications, National University «Zaporizhzhia Polytechnic», Zaporizhzhia, Ukraine, e-mail: anikinps@zntu.edu.ua, ORCID: https://orcid.org/0000-0001-6767-784X*