Checking of convergence of the finite element model for the software complex Simufact Welding with the real experiment using the method of additive manufacturing WAAM

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Wire and arc additive manufacturing (WAAM) is the most prospective methods for additive metal production, because it provides high productivity and low expenses for raw materials. High consumed process energy causes significant residual stress and deformation of billets. This paper describes thermomechanical behaviour of a multi-layer structure for a simple geometric figure (a rectangle), which was manufactured via WAALM process. Thermal-elastic and plastic model using the software complex Simufact Welding, based on the developed stationary thermal analysis, was used in this research. This approach to simulation displays essential advantage relating to the time of calculation. Temperature simulation and prediction of distortions are verified via comparison with the experimental results. Stress values along the whole cooled wall are uniform, with very slight influence of previous layers on consequent layers. The optimal temperature in a transit delay is determined.
Key words: wire and arc additive manufacturing, temperature between layers, control, quality, residual stresses, simulation.
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Introduction

Additive manufacture is an up-to-date technology for production of complicated 3D components of machines and mechanisms directly from the data of a 3D model, what increases productivity and technological flexibility in comparison with conventional production processes. Wire and arc additive manufacturing (WAAM) is based on welding arc as a heat source and is finalized in growth of the components from wire [1–4].

There are several factors [2–8], which control evolution of microstructure during WAAM as a multi-physical appearance. Taking into account this conclusion, it is important to understand interaction between microstructure and mechanical properties, what helps to choose WAAM process for various applications. Material state during crystallization and cooling is assessed for forming of molten roll and microstructure, it was examined in many researches [1–4]; influence of cooling rate on microstructure variations during growth of metal layers via WAAM method is shown.

Totally more than 60 researches, where their authors considered influence of heat on macro- and microstructure as well as mechanical properties of deposited metal layers using WAAM method, are in the open access. Analysis of these works displays that practically all products (nevertheless of material for growth), which were manufactured via WAAM, are impacted to thermal problems occurred by large heat amount; billets are subjected to heat effect during the process, what can lead to excessive residual stresses and substantial deformations.

The authors of the works [2, 3, 6, 7] noted that heat amount, which was introduced during welding, as well as heat conductivity and specific heat capacity of the main material or materials have the basic importance for determination of the cooling rate. In its turn, it is very important for control of solid phase transformations during cooling, which can occur in heat affected and melting areas. Then they testify that microstructural grain refinement with increase of welded seam strength and lowering of residual stresses is observed during multi-pass of multi-step welding. The main causes of these appearances, based on the opinions [2, 6, 7–11], are as follows: each consequent thermal cycle refines of “normalizes” grains of preliminary deposited metal; a previous pass is characterized by the effect of preliminary material heating and, thus, cooling rate decreases and consequent thermal cycles can release residual stresses caused by the previous passes. In multi-pass welding, there is no common opinion about the way of heat input analysis. However, the universally accepted concept, which was approved for designing and in specifications of welding procedures, concludes in registration of heat input for each single pass and in calculation of an average value for consequent use for process qualification.

The authors [1–7] think that the concept of heat input is well-known and has a linear dimension, and in additive manufacture it is mainly varied among the research groups, especially among those which use laser systems. At present time there is no general determination for qualitative assessment of heat that is introduced in each deposited layer, what is basic for control of solidification and transfer of molten metal for the case of using charging systems for powder or wire.

At the same time, solution of thermal problems in heat accumulation between weld beads is evident – it concludes in setting the pauses between deposition operations, to let weld beads cool at least by 50–80 °C during this time, transferring heat in the environment.

On the opinion of the authors [8, 9], a downtime period controls the temperature between passes, i.e. the billet temperature in the beginning of welding deposition of the following layers. It is shown that if we increase downtime period during forming, we can decrease the value of residual stresses due to decrease of the temperature between passes.

At present time, two basic methods are used for planning the downtime period in WAAM processes: choice of fixed downtime and monitoring of substrate temperature. In the first case, the fixed downtime period is introduced in the end of deposition of each layer in the program of the component deposition. This technique allows cooling of the billet; however, it requires a series of multiple preliminary experiments for establishment of correct downtime period. In addition, the fixed downtime period can't provide supporting of the constant temperature between the passes. It is connected with the mechanism of heat transfer from the bath with melt to the billet, where heat conductivity in the growing direction is the most important heat flow; the height of billets, i.e. number of previously deposited layers, has essential influence on this heat conductivity. Thereby it is necessary to increase the downtime period during welding deposition in order to provide equal temperature between the passes.

Usually it is achieved by the second method, i.e. by control of the substrate temperature using a sensor (as a rule, a thermocouple). After deposition of a layer, the process is stopped until the thermocouple signal achieves the preset value. Accuracy of this method is not a constant value, because gradual growth of deposited metal is connected with a temperature measurement error in molten metal bath, which is caused by increase of the distance between current layer location and substrate with mounted thermocouple.

Numerical simulation demonstrated lately its potential as reliable and simple tool for quality prediction of the components, which are manufactured via WAAM processes [1]. Finite element method can be used for analysis and prediction of residual stress and deformation during additive production [8–10], what allows developing the methods for decrease of thermal deformations during WAAM process.

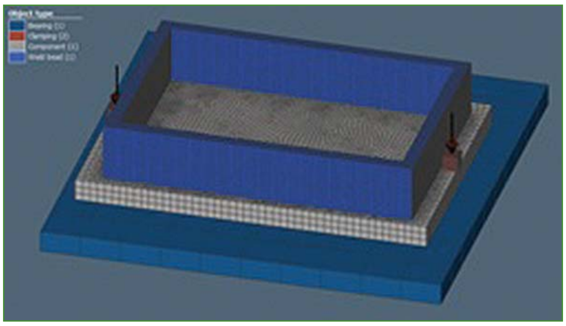
The authors think that there is nor universally available literature describing systematic researches of delay influence between the layers on microstructure and mechanical properties of steel constructions manufactured via WAAM method. Actually, the simulation theme is not considered for the main part of steels, which has priority importance for obtaining deeper knowledge about physics of the process, for elimination of mistakes during selection of operating parameters, for prediction and prevention of origination of defects or undesirable microstructures, for improvement of mechanical strength of components and for ensuring WAAM development for the new materials and supplements.

Thus, this research is aimed on the attempt to provide simulation of WAAM process with holding between passes and layers and with use of the software complex Simufact Welding, with final comparison of the obtained results with actual values.

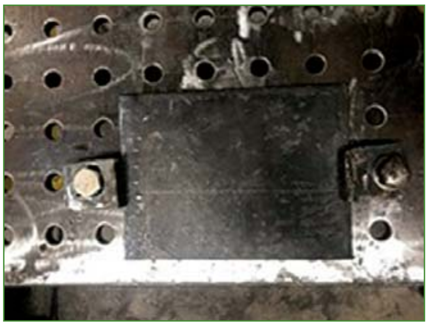
Materials and methods of the research

The stage of simulation. Simulation of the component growth process using the software complex Simufact Welding (7.1 version) in the module Direct Energy Deposition (DED), which was specially developed for process simulation of addition growth of components using WAAM technology, was carried out before the real experiment. The university has the license for this software. Geometry of the billet, which is planned to be obtained during the real experiment, was created – it is a basic plate with deposited welded-on rectangle (**Fig. 1*a***). Then a hex mesh with cubic elements, with dimensions 1.75×0.66 mm for deposited welded-on trajectory was built using the Apex program (allowing to create a final element mesh) of MSC company. The mesh with dimension 1.75 mm was also created on the surface of a basic plate, according to dimensions of a deposited welded-on square; in other parts of a basic plate the value of final elements was 4 mm (in order to decrease time of calculations). Cubic elements were selected for conduction of calculations, because just this kind of finite element mesh allows obtaining of the most reliable data, meeting the real parameters. Fig. 1*a* displays the view of the model with the table, where the basic plate is fixed by clams. Heating source, which was used in the software complex Simufact Welding and was suggested in Goldak works [14], is based on Gauss distribution of energy density in space. Based on the data of the researches [6, 7, 15–19], the optimal delay time between deposited welded-on layers is within the range 30–120 s. We accepted the minimal calculation time 30 s in our calculations.

Experimental stage. Structure of grown rectangle was created with WAAM assistance, using the robotized welding complex consisting of the robot CRP RH14-10-W and energy source for welding Megmeet Arsten Plus 400 [6, 7]. Wire Sv-08G2S with diameter 1.2 mm, produced by ESAB company, was used for growth of a rectangle; gaseous mixture Ar/CO_2 82/18 was used as protective gas, while gas feed remained constant (15 l/min) during the whole process. The square was deposited via welding on the basic plate with dimensions 191×134×12 mm; this basic plate is manufactured from carbon steel St3 with usual quality. Parameters of the



a



b

Fig. 1. View of the model for calculation (*a*), basic plate for the experiment (*b*)

welding process were following: welding current 150 A, voltage 19 V, welding speed 8 mm/s, and it was selected to provide high values of a deposition welded-on coefficient and process productivity. The process efficiency is 0.85, what is a standard value of the efficiency factor for mechanized welding in the atmosphere of inert gases. To provide cooling of a component between deposited welded-on layers, cooling duration 30 s was preset. The temperature between layers was measured by pyrometer Termoskop-800-2S with measuring error ± 25 °C. Pyrometer was tested for the samples, which were heated in the furnace to 600 °C with the measuring step 50 °C. The basic plate is pressed to the table by two clamps with force 5kN. The component surface was cleaned preliminarily by hand tool with removing scale and corrosion. The points were applied on the component surface and trajectory of robot motion was preset according to these points. Parameters of welding and motion direction were preset in a welding robot using remote control sensor; a module of multi-pass welding was used for displacement to preset layer height.

The results of simulation and experiments

To coincide the date with a real experiment, the following data were selected from the simulation results: variation of the temperature during certain time period on the surface of the basic plate in its middle and final deformations of the basic plate in its corners.

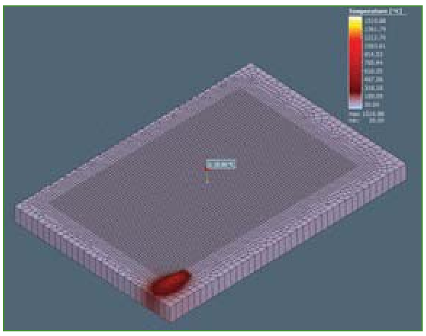
The point, where temperature measurement during simulation and real experiment was conducted, is shown in the **Fig. 2*a***. Variation of the temperature in the points of trajectory beginning and finishing was determined after simulation. The model temperatures just after welding are displayed in the **Fig. 2*b***.

The stages of simulation (**Fig. 3**) and real experiment (**Fig. 4**) were then conducted with the same welding parameters and procedures; the temperatures in the beginning and finishing points of welding seam were also measured. The graph of temperature varying in the beginning and finishing points of welded joint, for mathematical simulation and real experiment, is shown in the Fig. 3*a*.

Final deformations of the basic plate in its corners during simulation are displayed in the Fig. 3*b*. Deformation of the basic plate, which is equal to 2 mm in the corners of the this plate, were also measured after finishing of the real experiment and complete cooling of a billet; surface grinding of the surface with obtained geometry was done as well, and the corresponding pictures were captured. The side surface of a rectangle wall after finishing of deposition welding process is presented in the Fig. 4*b*. Fig. 4. The real grown-up rectangle with 18 layers (*a*) and growth trajectory kind after welding deposition – side view (*b*)

It was noted that an error is accumulated and geometry of the deposited welded-on layer is varied during deposition, due to absence of variation of the points of trajectory beginning and finishing. The view of surface irregularity along the trajectory is shown in the **Fig. 5**.

Variation of geometry in the end of the process of forming of bead-on-plate welds and error accumulation due to features of the welding process (flow of molten metal in a bath) are mentioned in [7]. The authors of this research suggested



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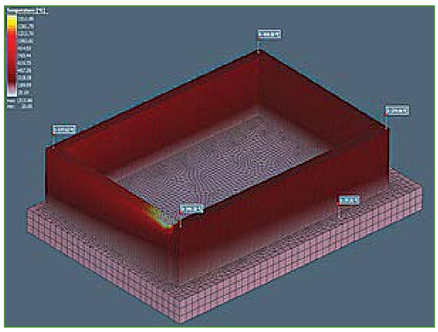

b

Fig. 2. The point of temperature measurement in time during simulation and real experiment (*a*) and temperature measurement in a component just after welding finishing (*b*)

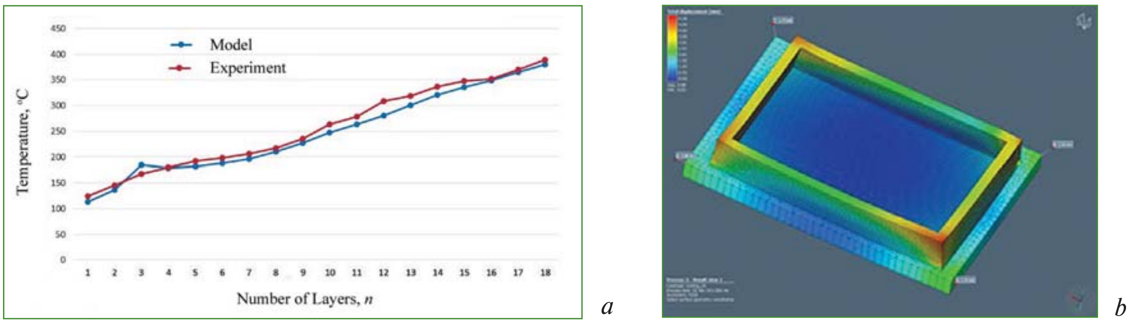

Fig. 3. The graph of temperature varying for mathematical simulation and real experiments (*a*) and displacement of corners of the basic plate after growth (*b*)

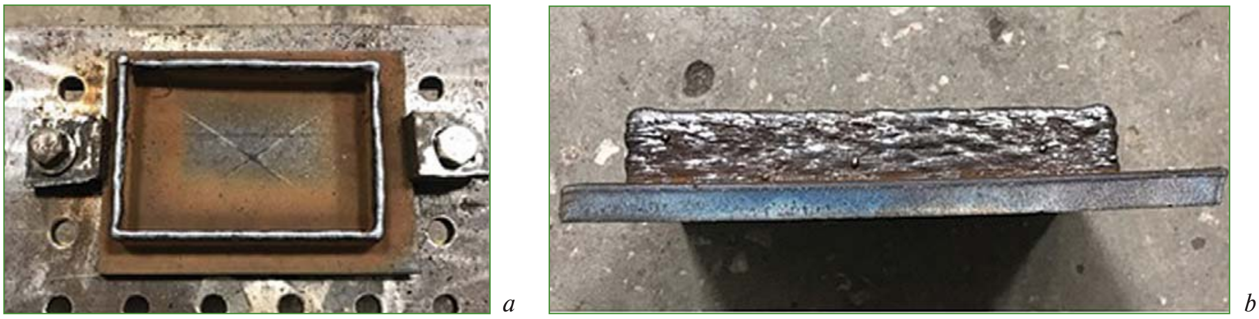

Fig. 4. The real grown-up rectangle with 18 layers (*a*) and growth trajectory kind after welding deposition — side view (*b*)

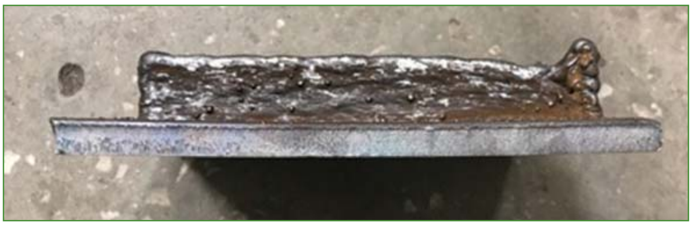

Fig. 5. Geometry variation during growth of the component

to vary the starting and finishing points of the welding process in order to prevent this error accumulation and to use this technique also in growth of closed geometric figures, such as cylinder or square.

When finishing 18 layers, the robot was quickly retuned and growth according to the preset geometry was continued. The finished and ground component is displayed in the **Fig. 6*a***. Temperature measurement after overlapping of each layer was conducted experimentally and shown in the **Fig. 6*b***. It can be seen that temperature rise takes place during growth of all 18 layers, then the temperature stabilizes within the range 230–260 °C. In the end of growth process, temperature even decreases to 200 °C with increase of height of deposited welded-on metal.

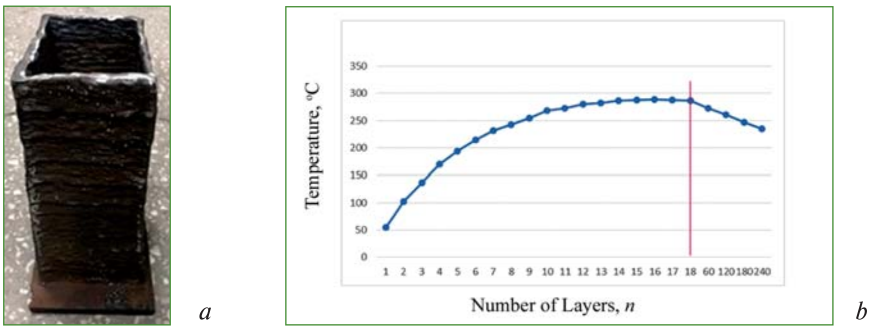

Fig. 6. The obtained component consisting of 240 layers after release of clamps (*a*) and temperature values during the real experiment (*b*)

Mathematical simulation of the process using the software complex Simufact Welding was carried out for optimization of this process and selection of the most preferable location of clamps. Two calculations with various locations of clamp devices were executed. In the first case, the clamps were located in the same way as in the real process (**Fig. 7*a***). Force values at these clamps were 3 kN for each of them. In the second calculation, additional clamps in the corners of the basic plate were mounted with force also 3 kN; the model for this calculation is shown in the **Fig. 7*b***. Calculation for 4 layers of deposited trajectory was conducted during simulation, then deformation in the edges of the basic plate is determined. The view of deformed components is presented in the **Fig. 7*c*** and **Fig. 7*d***. Simulation with 5 clamps was also carried out, the view of the components after the second experiment is shown in the Fig. 7*d*.

It can be concluded on the base of the obtained simulation data, that mounting of additional clamps in the corners of the basic plate decreases deformations, and that a component should be fixed in maximal possible number of points in order to further deformation decrease.

Pictures of the manufactured components of an exhauster casing with two clamps is displayed in the **Fig. 8**. Deformation of the basic plate until release of clamps was measured after complete component cooling and equalizing of the upper layer; they made 4 mm from each side. Then deformation of the basic plate was also measured after release of clamps, its values were 9 mm from each side. Displacement of trajectory and origination of stresses in metal occurred due to high thermal shrinkage and transfer of walls. Maximal displacement was observed for the front walls, it was 9 mm from location of the first layer.

The values of deformations during three experiments are displayed in the **Fig. 9**.

It is possible to assess width and height of deposited bead-on-plate welds during simulation (**Fig. 10**). It can be seen that external wall topography, which was applied between layers with retarding time 20 s during experimental deposition welding (see Fig. 4 and Fig. 5), is heterogeneous due to the effect of heat accumulation. At the same time, wall topography, which was applied between layers with retarding time 30 s and 60 s, are homogeneous.

Fig. 10 displays that the wall height increased by 13 % with enlargement of retarding time between layers from 20 s to 40 s, while the wall width decreased by 23 % with enlargement of retarding time between layers from 40 s to 80 s.

Decrease of the wall width was 13 % and 5 % for enlargement of retarding time between layers from 20 s to 40 s and from 40 s to 80 s respectively. Decrease of the wall height can be connected first of all with reduction of the temperature of preliminary heating on the surface of a previously grown layer, what leads to lowering of deposition efficiency. From the other side, decrease of the wall width with enlargement of retarding time between layers is mainly connected with

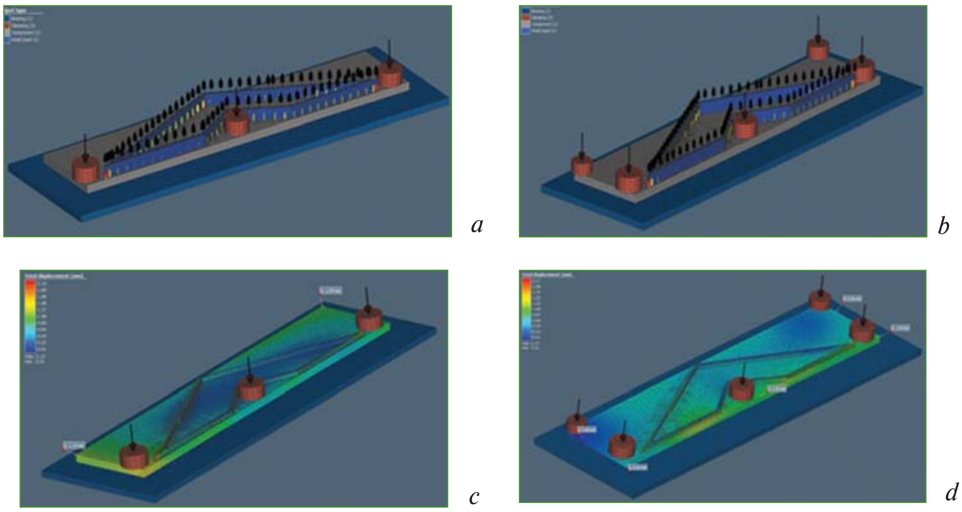

Fig. 7. The results of model deformation with clamps via the first variant (*a*, *b*) and the second variant (*c*, *d*)

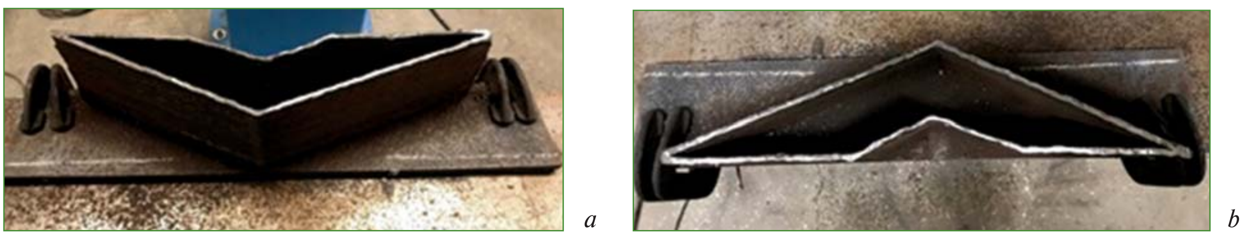

Fig. 8. The picture of grown exhauster casing — front view (*a*) and top view (*b*)

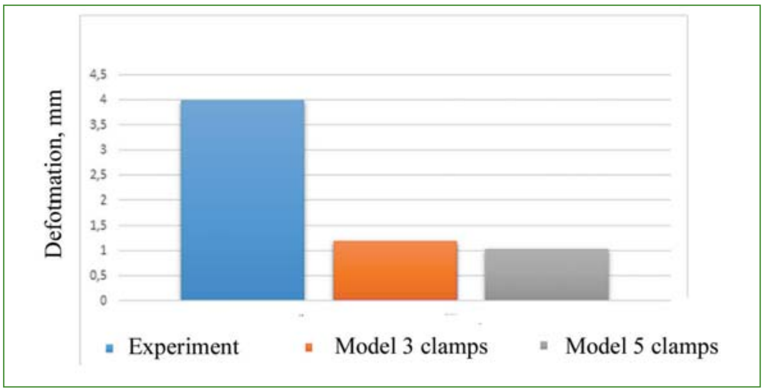

Fig. 9. The values of deformations during three experiments

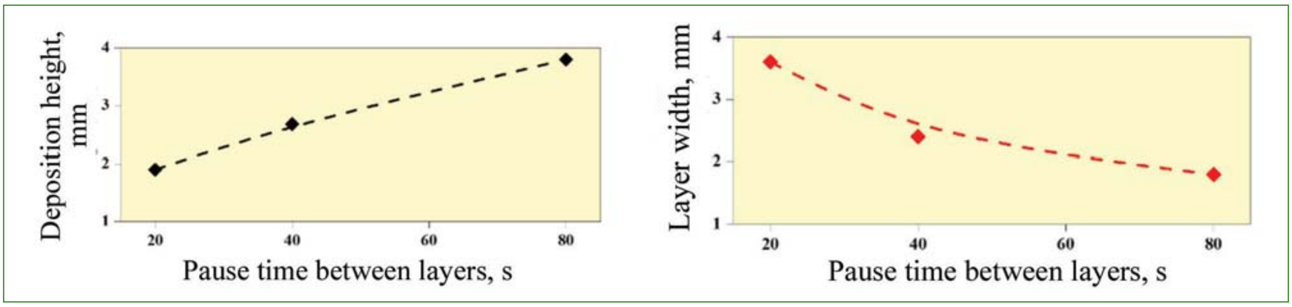

Fig. 10. Influence of the retarding time on height and width of deposited bead-on-plate welds

lowering of external flow in a melt bath due to reduction of the temperature of preliminary heating.

Results and discussion

It can be concluded from the data obtained during simulation and a real experiment that too high error of temperature measurements takes place. Maximal values of the temperature gradient during simulation and a real experiment are used for determination of the absolute and relative errors. The concept of modifying of the efficiency factor for the heating source with increase of layers, in order to compensate the increasing volume of a welding bath, is explained in the research [15]. It concludes in correction of the main parameters of welding process until the consequent layer will repeat the previous one. The authors of this work think that this event appears to the 12–13 layer of deposited welded-on geometry. As for our experiments (see Fig. 6*b*) it appears to the 15–18 layer.

The concept described in the research [15] was not used in this work during simulation, because elevation of a robot, executing deposition welding during practical experiments with deposition of walls with length up to 250 mm, was implemented to the same height. It means that used technological parameters allow saving stable and non-varying layer height.

Accuracy of prediction of mechanical response for a billet is evaluated via comparison of deformed upper surface of an actual plate and simulated one. Experimental and simulated surfaces are compared in the Fig. 7 and Fig. 8. These results correspond to those presented in the researches on WAAM simulation [10–19]. Such accuracy level allows to assess effectively process simulation for optimization of its technological parameters and development of strategies for deformation softening during growth.

The next aspect to be underlined is a heat source model for WAAM, which is presented by a double Goldak ellipsoid, while a proposed heat source is based on heat supply during welding as a function of heat generation, allowing control of total power supplying to substrate and filling metal. Indeed, the part of arc power during WAAM process is supplying directly to substrate, while the other part is consuming for melting of filling metal, with consequent transition to a billet via enthalpy of filling molten metal drops [14]. It is suggested to a first approximation that 50 % of total power is supplying to substrate and other 50 % – to filling metal [14]. As soon as the Goldak heat source means Gauss distribution, achievement of such power distribution for a heating spot requires tuning operation for dimensions of an ellipsoid half axle (see Table 1, Fig. 1*b*), which are usually selected in correspondence with dimensions of a molten bath.

When manufacturing a real component (see Fig. 8), effective wall width and layer height are the basic geometric parameters to be controlled. These dimensions are inherited from a welding bath, similar to strengthening of a welded seam. They can be considered as a result of interaction between arc power, transition speed, deposition welding speed, temperature between passes and material properties. Deviation of dimensions in created structures depends first of all on temperature accumulation during deposition, which in its turn controls external flow of molten bath. Temperature accumulation can be controlled via varying the temperature of preliminary heating, which is accessible on the previously deposited layer before application of the following layer. The temperature of preliminary heating, in its turn, is controlled by varying technological parameters or process conditions. Temperature control between the layers can also help in oxidation control during deposition, especially working with reactive materials [18]. Maximal temperature gradient during deposition welding was calculated for each layer, when a heat source passes through the layer center. Thermal properties of the a.m. research were reproduced in various conditions.

It was established during our investigations that more short retarding time between the layers leads to more high temperature of preliminary heating, what has the effect on deposition of consequent layers. Additionally, as soon as deposition transits from the lower layer to the upper one, the temperature of preliminary heating also increases for the definite retarding time. It occurs mainly due to quick heat dissemination in the lower layers, owing to the substrate effect. As soon as deposition transits to the upper layer, heat accumulation increases and speed of heat dissemination decreases. And when deposition transits from the lower layers to the upper ones, the wall width increases, what is caused by variation of molten metal viscosity during deposition, because viscosity depends on the temperature.

Variation of microstructure and mechanical properties can be also explained using the values of the temperature of preliminary heating, which are presented in our researches [6, 7]. The lower temperature of preliminary heating with higher retarding between the layers leads to more high temperature gradients and more high cooling rates; it finalizes consequently in more fine-grained structure and better mechanical properties [15–17].

It should be noted that use of the software complex Simufact Welding is possible for simulation of the processes of additive growth of components using an arc heating source. Simulation of durable growth process is problematic, because it requires much time and a high-power computer.

Conclusions

When modeling the components with simple geometric shape (such as rectangle), made of steel with various values if retarding between the layers using WAAM, the following conclusions can be done:

1. Improvement of density between deposited welding layers by 10–30 % is observed for the sample with high retarding time, while wall width and height decrease by 5–10 % with increase of the retarding tome between the layers owing to lowering of the molten bath temperature.

2. Numerical simulation displays that the temperature of preliminary heating lowers with increase of the retarding tome between the layers, what leads to variation of geometry, microstructure and mechanical properties. Simulated heating temperature of deposited welded-on metal corresponds well to the experimentally obtained temperature values.

3. It is necessary to fix components in maximal points in order to provide lowering of deformations.

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