Digital visualization of thermal processes accompanying welding of small-diameter pipes

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Abstract. The work investigates the specificity of the thermal processes occurring during formation of a molten pool in curvilinear specimens. The process is exemplified by welding of small-diameter pipes. A numerical 3D-model of the interaction of a moving heating source and thick-walled pipes of various curvature was built. The material, diameter and thickness of pipes were selected as per active standards. The numerical calculations were performed. The practical experiment was performed using argon tungsten-arc welding. The results establish the effect of the welded part geometry on the dynamics of thermal processes in the molten pool.

1. Introduction
At present, the welded structures from small-diameter pipes are widely used in the industry (oil and gas, chemical, machine building, etc.), to create various articles for household purposes (metal furniture, advertisements, fences and other) and in various equipment (direct incuts into pipelines for mounting pressure gauges, piping of valve stations, pulse tubes for valve control). The household articles, in addition to operational requirements, should meet pleasant exterior requirements.

Interestingly, literature sources pay insufficient attention to welding of curvilinear surfaces of small diameter. Though, it is well known that welding seam formation in such articles is accompanied by metal overheating, as compared to welding of flat specimens of the same thickness. It is believed, that overheating is imminent due to low heat dissipation inside welded pipes. In this connection, the manufacturing of relatively small critical structures often involves more labor-intensive mechanical processing (turning, machining, drilling, etc.), for instance in bearing production.

The aim of the work is to build a computational model for visualizing the formation of curvilinear welded joints and distinguishing the effect of the surface curvature on selection of welding regimes.

Materials and Methods.
The study compares welding of 09G2S steel pipes (as per GOST 19281–89) with welding of plates. The calculations were performed by argon-tungsten-arc welding as per GOST 2246–70. Curvilinear welding models were created by special software developed and tested by the authors for this work.

The calculations were validated by real experiments.

2. Problem solution method
Small-diameter pipes are usually welded by manual argon tungsten-arc welding. The standards allow welding flat parts without a filler wire; conversely, small-diameter pipes are welded only with a filler
wire. Fig. 1 depicts steel specimens welded with and without a filler wire. Evidently, in the latter case, there is no weld bead, the seam dropped inside the pipe due to lacking heat sink and metal overheating. The overheat is known to be diminished by increased welding speed. However, in manual welding it is hard to measure and increase the speed.

![Figure 1](image1.png)

**Figure 1.** Appearance of steel pipe welding seam: a) two-pass welding with filler wire; b) one-pass welding with filler wire; c) welding without filler wire.

At the same time, finding the arcing regimes that provide high-quality connection without a filler wire is of large interest. This is possible when the melt viscosity is sufficiently high and the melt has enough time to crystallize before it falls into the pipe under the gravity. This problem was solved numerically using finite difference method [1]. The contact zone of the welding parts was assumed to be absolutely smooth. In the calculations, it was distinguished by a line or plane of symmetry. Taking into account that the heat processes in the contact zone of arc with pipe surface are independent of the electrode movement direction, only linear trajectories of movement along the cylinder generatrix were studied. The calculation used a mathematical model of spatial heat conductivity problem with due regard to the moving heating source, presence of different states of aggregation (solid, liquid, gaseous, plasma) and structure-and-phase transitions [2]. The problem was solved in Cartesian rectangular coordinates by dividing the volume into cubic cells of different dimensions that were used to compose cylindrical panels of a given diameter (Fig. 2).

![Figure 2](image2.png)

**Figure 2.** Example of formation of calculated cylindrical panel: a) plane section for 100-mm pipe with wall thickness of 2.5 mm; b) 21.6-mm pipe fragment with wall thickness of 1.8 mm.

The calculations were made for pipes of different diameter: from 14 to 100 mm. The thicknesses were set as per GOST. Arcing regimes were selected to achieve a burn-through with the width of no less than 1–1.5 mm from the outside. The weld width was not specified; it was a consequence of preset conditions.
3. Digital Visualization Results and Discussion

When solving a problem of numerical modeling of heat processes in a molten pool, a particular difficulty is to output the results and represent the dynamics of spatial phenomena on a computer monitor. The main complexity is connected with a large volume of spatial-temporal information to be processed which appreciably inflates with increased number of input and output model parameters. The input parameters are arcing regimes, geometry of welded parts and physical material properties. The output parameters are the geometry of the welded joint, number and dimensions of the zones of structure-phase transitions. The compactness and readability of the whole information volume affects the understanding of phenomena hidden from an observer.

We will omit the methodology of information processing and give the study results. Some differences in welding of flat specimens and small-diameter pipes were distinguished. First of all, the mechanism of initial molten pool formation is different. For flat specimens, the molten pool shape in the cross-section is known to be semi-spherical or semi-elliptical. In pipe-shaped specimens with large curvature, it is pear-shaped. This is explained by different contact zones of the arc with the surface of the cylindrical panel and flat plate. Hence, the heat fluxes inside the metal will be different as well.

Fig. 3 depicts the molten zone profiles in horizontal sections of 33.5-mm pipe with the wall thickness of 2.8 mm at different distance below the surface.

For the purpose of comparison, we present the molten zone profile in a plate with the same thickness. Arcing regimes for the pipe were as follows: current I = 90 A, voltage U = 12 V, speed V = 155 mm/min. However, they were not suitable for plate welding, because the weld width on the back side turned out to exceed the standards, so the parameters were adjusted as follows: current I = 125 A, voltage U = 12 V, speed V = 200 mm/min.

![Figure 3. Molten zone in horizontal sections of weld at different distance below the pipe surface: a) 0.2 mm; b) 1.0 mm; c) 2.8 mm; and in plate d) 0.2 mm](image)

The calculations also revealed that the curvature of welded specimens affects the shape of the temperature front. It flattens with decreasing pipe diameter (Fig. 4).

![Figure 4. Temperature fields in the subsurface zone at different moments of time from welding beginning: a) and b) cylindrical panel; c) plate.](image)
To assess the validity of the calculations, line welding of a 33.5-mm steel pipe was performed at regimes described above and without a filler wire (Fig. 5). The pipe was made of 09G2S steel.

![Figure 5. Photo of the weld: top view (left), bottom view (right).](image)

Thus, the experiment has shown, that the arcing regimes were calculated correctly in general. The filler wire was not required; the weld seam formed without the melt dropping inside the pipe.

4. Conclusions
The work has suggested a numerical method for calculating heat processes accompanying the welding of nonlinear specimens in Cartesian rectangular coordinates. Such approach allowed visualizing the dynamics of the molten pool formation in small-diameter pipes and, most importantly, provide adequate comparison with similar processes when welding plates. The work has established the effect of welded specimen geometry on the thermal processes in the molten pool. The real experiment has testified the possibility to weld small-diameter pipes without a filler wire in the case of correct calculation of the arcing regimes.

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