Investigation of thermal and deformation processes in the welding of shell structures made of carbon and high-alloy structural steels

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Abstract. An experimental study of thermal processes in the welding of two intersecting shells of low-alloy structural steels of increased strength was carried out. As a prototype, a welded structure consisting of shell elements with different wall thicknesses was chosen. The features of the welding process are identified, which include: multi-pass manual welding with a breakdown of the joint contour into several sections. The results of studies of thermal and deformation processes are given taking into account the features of the welding conditions and the formation of the weld. Qualitative and quantitative estimates showed that minimizing the residual stress state of the welded structure can be achieved by the optimal choice of welding conditions.

1. Introduction

In power engineering, one of the most common designs are pressure vessels (steam boilers, steam generators, etc.), which must meet the conditions of strength, stability, tightness, corrosion resistance, etc. as a rule, they consist of shells, spherical bottoms and nozzles, the connection of which is made by welding. Features of the constructive form of such blanks are dictated by the technological necessity of procurement production, due to the use of appropriate equipment, forming tools, the flow of current technological regimes. As a result, there is a problem of compliance with the equidistant condition of the entire structure as a whole.

When designing such structures of low-carbon or alloy steel, it is assumed that local deformations by themselves cannot exhaust the reserve of plasticity of mild steel and, therefore, cracks can not be formed. In fact, a sharp drop in thickness at the weld joints of individual parts of the bearing housing leads to the formation of local zones with high values of thermal stresses and strains [1]. The heterogeneity of the shell structure leads to an uneven distribution of the temperature gradient between the front and inner surfaces, one of which experiences tensile stresses, the other on the contrary – compressive. In addition, the mechanisms of shrinkage stresses, which together with the current force factors in operation can be "dangerous" and contribute to the formation of microcracks and further crack development, are not sufficiently studied.

Currently, there are many works devoted to the theoretical study and mathematical modeling of thermal processes adapted to the welding conditions of spatial shell structures [1-7]. Very important in them is the formulation and solution of the temperature problem, which allows to determine the temperature stresses in the zones of technological influence.
In practice, thermal welding processes are largely determined by: welding method; electrode heating current; speed and direction of movement of the heat source; protective environment of the weld pool. With the chosen method of electric arc welding, the modes of the welding process are the main ones in the manufacture of high-quality welded joints [8]. Therefore, the development and implementation of experimental methods for the study of temperature fields and deformations in the zones of technological influence remain urgent tasks of manufacturing welded structures of high quality.

2. Substantiation of research methods and experimental work
The study of thermal processes in the welding of two intersecting shells of low-alloy structural steels of increased strength was carried out. Type is of connection-angular, non-rotating, welding method is manual arc welding with coated electrodes.

Note that the distribution of intrinsic stresses in the welded joints of shell structures has some features from similar stresses occurring in the plates. This concerns the nature of thermal stresses caused by the formation of temperature fields in the narrow zone of the weld [1]. The factors of influence include the structural shape and material properties of the welded elements, which largely determine the method of welding [8]. Structural transformations in welded metals significantly change the nature of stresses in the zone of plastic deformation [3, 7].

We highlight some features of the welding process. Multi-pass welding with overclocking of the weld is carried out. The formation of the weld in this way allows you to completely cover the gaps and ensure the integrity of the structure. This in turn leads to an increase in the level of residual stresses in the heat-affected zone of the welded joint [1].

Seams are performed manually with a breakdown of the connection contour into several sections. The uneven movement of the point heat source along the connection contour leads to an uneven thermal stress state of the heat-affected zone and its deformation. It is necessary to maintain the stability of the arc length. Increasing the arc length causes deterioration of its stability, increases fumes and metal spatter, contributes to the saturation of the seam with nitrogen and oxygen of the air and reduces the depth of penetration [8].

The study of deformation processes was carried out in the welded joint "shell – plate", which is widely used in the construction of power devices, Fig. 1. Such a connection can be conditionally considered as a connection of a cylinder with a flat shell. The material of the plate is low-carbon steel 20, the material of the shell (pipe) is high-alloy austenitic steel. The technological properties of these steels for weld ability are good.

In accordance with the typical welding process, the recommended welding current values range from 20 to 70 A per welding pass. Thus, for one pass of an electrode at welding of angular connections depending on value of size of welding current the effective thermal power can vary within 22 – 32%.

The choice of a specific value of the welding current corresponds to certain parameters of deformation and displacement due to the temperature fields of the driving highly concentrated heat source. This largely determines the strength of the weld and high quality under all other equal conditions. The experimental work was as follows.

Studies of thermal and deformation processes of the selected sample were carried out under different conditions of thermal loading on the welding current: with a decrease and increase in the welding current by 6% within the normal regime. Carried out the five weld passes, welding current was varied from 150 – 170 A.

During the imposition of rollers in the welding of shell elements changed welding modes, i.e. welding was carried out on the "slow" and "fast currents". In reference points of a contour of a welded seam in the direction of movement of an arc after each welding pass temperature was measured by the contact thermometer TK-5 at certain intervals of time. Zones of uneven temperature distribution were identified. This was especially true of the last sector of the seam formation.
2.1. Results
Uneven distribution of weld stresses by nature (compressive and tensile stresses) in the weld and by levels in the connection circuit is noted.

Figures 1 and 2 show the weld roller overlay schemes and the rate of temperature change along the circumference of the pipe.

Figure 3 shows the rate of change along the pipe circumference and height. Temperature measurements were taken at points 4, 5 and 6.

![Figure 1](image1.png)

Figure 1. Sample and scheme of welding seam: 1 is base; 2 is pipe.

![Figure 2](image2.png)

Figure 2. Rate of change along of temperature the circumference of the pipe.

![Figure 3](image3.png)

Figure 3. Rate of change along of temperature the circumference and the height of the pipe.
Established (Figure 2) that under the welding conditions of the 3rd and 5th pass (welding current: 170, 160 A) the temperature gradient varies slightly; its value is more uniform. Heat distribution is carried out in different directions from the hottest point "4" to the point "2". During the last pass, there are sharp changes in the temperature gradient from "4" point to "2" point in different directions. Consequently, the vicinity of the heat-affected zone 1-2-3 is most prone to the formation of hot cracks.

Radiographic and metallographic inspection of the weld revealed the following. The presence of cracks in the previously assumed zone in the vicinity of point "2" is observed.

By pipe height, Figure 3, there is a maximum (peak) value of the temperature gradient at the point "5" with a sharp drop to the point "6". Uneven cooling along the height of the pipe leads to warping of the structure as a whole. There is a deviation of the generatrix of the cylinder from the perpendicular, and quite significant.

3. Conclusions
Thus, the conducted experimental studies made it possible to qualitatively and quantitatively assess the effect of the heterogeneity of the geometric parameters of the welded joint elements on the thermally stressed state of the structure due to the inhomogeneous high-gradient local temperature effect in the zone of technological influence. Minimization of the residual stress state of the welded structure can be achieved by the optimal choice of welding conditions.

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