Influence of boundary conditions on the strengthening technology of a welded joint with a ball-rod hardener

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\textbf{Abstract.} The article deals with the problem of assessing the influence of the boundary conditions for fixing a plate with a welded seam on the stress-strain state during hardening with a ball-rod hardener. Welded joints are currently a trouble spot of the destruction of heavily loaded structures. Analysis of the microstructure and strength characteristics of the welded joint of 09G2S steel showed that in the fusion and heat-affected zones, the strength decreases due to temperature effect. The problem of modeling the strengthening of a welded joint with a ball-bar hardener under various conditions of plate fixing: with a free and fixed lower face is considered. The FEM model is constructed and the comparison of the conditions of plate fixation is carried out, which makes it possible to assess the degree of hardening and to assess the residual stresses after hardening treatment. It is shown that strengthening of a plate with a free bottom face significantly changes the stress-strain state of the plate and redistributes residual stresses to the weld zone, where strengthening is undesirable.

\textbf{1. Introduction}

Ensuring the reliability of welded joints is an important task in construction and mechanical engineering. In recent years, the destruction of building structures [1], orthotropic steel decks [2], heavily loaded steel structures of road-building machines [3], etc. has become more frequent. The strength of welded joints is the object of many studies and determines the reliability of the structure.

When welding, steel changes its mechanical properties in complex ways. The weld is significantly heterogeneous and it is impossible to calculate this heterogeneity in advance. In work [4], the authors proposed a thermo-mechanical model of the weld based on the energy balance law using the FEM in the ABACUS software. The model made it possible to carry out thermal calculations during welding and obtain data on residual stresses in the weld zone. Despite some achievements, it is theoretically very difficult to predict mechanical characteristics; therefore, in practice, methods of operational experimental testing are used for heterogeneous media [5, 6].

In [7], the study aims to study the metallurgical aspects of a welded joint by considering various locations such as HAZ, weld metal and base metal. The properties of steel differ between the base material and the weld metal. Tensile test results have shown that the weld metal has a higher strength (and hardness) compared to the parent metal, but this is dependent on the correct welding procedure specification being used. In Figure 1 shows the distribution of microhardness in the welded joint zone.
Figure 1. Microhardness distribution along the welded joint (according to [4]).

It can be seen (Figure 1) that in the zone of the weld seam the hardness has the highest value, in the heat-affected zone there is a decrease in hardness by about 69 HV, and then, with distance from the weld axis, the hardness increases to 175 HV of the base metal.

The effect of welding on the change in the microstructure and mechanical characteristics of a welded joint was carried out in [8]. The low carbon steel was welded using a shield metal arc welding method with an E7016 electrode with a diameter of 2.6 mm. Charpy impact testing, Rockwell hardness testing and microstructure monitoring in the weld zone, including the base metal, heat affected zone (HAZ) and weld metal, were then carried out. The results showed that the highest impact toughness in the weld metal zone is 251 J / mm², and the lowest impact toughness in the heat-affected zone (HAZ) is 119 J / mm².

Such inhomogeneity of the welded joint requires a HAZ hardening procedure for further use in heavily loaded structures. The hardening processing technology proposed in [9] and developed in the works of Tamarkin [10, 11] involves the use of a ball-rod hardener described in [12]. In cases of heavily loaded structures with welded joints, the heat-affected zone must be strengthened. A significant increase in the production of structures with welded joints sets the task of developing cost-effective technologies of high quality.

Numerical simulation using FEM in combination with a physical experiment was carried out in [13] for a fillet weld. This made it possible to predict the transient temperature distribution at fillet welds for the arc welding process. Changes in the properties of the reactor pressure vessel material caused by neutron irradiation were studied in [14]. The time-of-flight (TOF) neutron diffraction method was used to determine the distributions of residual stresses and microstructural changes in Charpy samples welded by arc welding, electron and laser beams. The lowest level of residual stresses in the areas of welded seams was found for a specimen welded with an electron beam with optimal parameters in comparison with other methods.

It can be seen from the above review that welded joints have zones of reduced strength either in the heat-affected zone or in the fusion zone. Strengthening of welded joints is associated with modeling problems of indentation of parts of a ball-bar hardener. The choice of the hardening mode, impact speed, and depth of the hardened layer remain unresolved. Thus, the article sets the goal of modeling...
the strain hardening of a welded joint and analyzing the influence of the conditions for fixing the workpiece or the structure itself when working with a hardener.

2. Materials and methods
Welded joint made of structural mild steel 09G2S is made as shown in Figure 2 (only half of the weld is considered due to symmetry). The plate thickness is 10 mm, the length from the middle of the weld to the boundary of the base metal is 40 mm. The problem of indenting a rigid spherical indenter into an elastoplastic medium, which is a welded joint, was solved by the FEM method. The radius of the sphere is 4 mm. Plate anchoring: all nodes lying on the axis of symmetry of the seam are fixed along x, that is, $U_x = 0$. All nodes lying on the $x = 40$ mm axis (that is, the right edge of the plate) are fixed with $U_x = 0$ and $U_y = 0$. In the process of indentation, the displacements of the spherical indenter are set step by step and the stress-strain state is determined at each step.

Consider a welded joint made of structural low-carbon steel 09G2S, as shown in Figure 2 (half weld due to symmetry). The X-axis will be directed horizontally along the bottom of the strip. The Y-axis will be directed vertically along the axis of the seam. The plate thickness is 10 mm; the length from the middle of the seam to the border of the base metal is 40 mm. Ball radius 4 mm. The load is set by the indenter displacement by a value of 0.3 mm in steps.

![Figure 2. Finite element model of a welded joint: on the left a) the lower edge of the plate is fixed; b) the bottom edge is not fixed; 1 - base metal; 2, 3 - heat affected zone; 4 - seam; 5 - indenter.](image)

The mechanical characteristics of the metal, such as the yield strength $\sigma_Y$ and tensile strength $\sigma_u$, the elongation $\delta$ and $E$, is the hardening modulus used in the bilinear model with isotropic hardening, in the welded joint zones were determined according to the method [15].

| N | Zone title | $\sigma_Y$, MPa | $\sigma_u$, MPa | $\delta$ | $E$, MPa |
|---|------------|-----------------|-----------------|---------|---------|
| 1 | Main metal | 280             | 430             | 0.34    | 441     |
| 2 | HAZ 2      | 250             | 360             | 0.4     | 275     |
| 3 | HAZ 3      | 300             | 450             | 0.25    | 600     |
| 4 | Weld       | 320             | 460             | 0.22    | 636     |

3. Results
The simulation results in the form of stress, strain and displacement fields were obtained for two stages: loading and unloading. In Figure 2 shows the fields of equivalent von Mises stresses in the loading stage. Comparing the graphs of the equivalent stresses for the plate fixed a) and not fixed b) from below, it can be seen that the boundary conditions significantly change the stress-strain state. For a fixed plate, the equivalent stresses have a pronounced symmetric field distribution. It is also seen that, at given loads, the role of von Mises stresses reaches the lower edge and is approximately 120 MPa. With this fixing, an indentation mode is possible, in which the HAZ material can be strengthened to the entire depth of the plate.
Figure 3. Fields of equivalent von Mises stresses at the loading stage: a) the lower flange is fixed; b) the bottom shelf is free.

The field of the stress-strain state of a plate with a free bottom edge is completely different. Figure 3 b) shows that von Mises stress fields are asymmetric. The zone of maximum stresses is displaced and is located not only at the point of application of the load, but also in the fusion zone in the region
where the weld meets the base metal of the plate. Affects the stress concentrator. The maximum von Mises stresses in this case are 10% less and amount to 335 MPa.

In Figure 4 shows the von Mises stress fields after unloading and show the residual stresses in the zone of the welded joint after strengthening.

Figure 4. Fields of equivalent von Mises stresses after unloading: a) the lower shelf is fixed; b) the bottom shelf is free.
It can be seen (Figure 4) that the pattern of residual stresses is also significantly different. For a loose plate, residual stresses are concentrated not only in the indentation zone, but also in the zone of the weld and HAZ. The lower edge is also hardened by compress stresses.

4. Discussion
In Figure 5 and 6 show graphs of equivalent von Mises stresses along the thickness of the plate along the axis of indentation at the stage of loading (Figure 4) and unloading (Figure 5)

**Figure 5.** Dependences of equivalent von Mises stresses along the plate thickness along the indentation axis at the loading stage: S_eqv Free for a plate with a free bottom face; S_eqv Fixed for insert with fixed bottom edge.

![Figure 5](image)

**Figure 6.** Dependences of the equivalent von Mises stresses over the plate thickness along the indentation axis at the unloading stage: S_eqv Free for a plate with a free bottom face; S_eqv Fixed for insert with fixed bottom edge.

Comparison of the dependencies in Figure 4 shows that with a fixed lower boundary, the von Mises stresses have a characteristic bend in the curve (Figure 5 S_eqv Fixed) and under the surface it increase in the loading stage. For the hardening of a plate with a free lower boundary, the picture is different. In comparison with the fixed edge, it can be seen that the stresses on the upper flange in the
zone of contact with the indenter are less by about 10%. Further, the stresses drop and have a significant decrease in the stress level in the middle of the plate, then increase again due to compressive stresses $\sigma_c$.

In Figure 6 shows the dependences of the equivalent von Mises stresses along the plate thickness along the indentation axis in the unloading stage.

It can be seen that the zone of significant residual stresses is under the surface at a depth of 1 mm for a plate with a fixed edge and 2.5 mm for a plate with a free bottom edge. At the same time, due to the compressive stresses $\sigma_c$, at a depth of 7 mm to 8.5 mm from the upper edge of the plate, the residual stresses have a surge and reach 73 MPa.

5. Conclusions
The problem of studying the influence of the conditions of plate fixing during strengthening of a welded joint with a ball-bar hardener is considered. The comparison is carried out on the example of a plate lying on a rigid base and with a free bottom face. A model of the interaction of a ball-rod hardener with a steel plate by the FEM method is obtained. It was shown that the conditions for fixing the plate play a significant role, both quantitatively and qualitatively. The von Mises stress fields differ significantly depending on the anchorage conditions. The results are obtained in the form of stress, strain and displacement fields. An analysis of the fields of equivalent von Mises stresses showed that with a fixed lower boundary, the von Mises stresses have a characteristic bend in the curve, and under the surface it increases in the loading stage. For the hardening of a plate with a free lower boundary, the picture is different. In comparison with the fixed edge, it can be seen that the stresses on the upper flange in the zone of contact with the indenter are less by about 10%. Further, the stresses drop and have a significant decrease in the stress level in the middle of the plate, then increase again due to the compressive stresses $\sigma_c$.

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