Consideration of welding stresses when welding technological rectangular cutouts

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Abstract. The article discusses the method for determining the prestress fields in hull structures with a rectangular cutout. After welding of the cutout the fields of residual welding stresses in the welding area are summed up with the prestresses. Methods of the mathematical theory of elasticity (the complex potentials in particular) are used. It is assumed that a uniform stress state is created in the plate in the absence of welds. Welding causes a disturbance in the uniform stress field. It is proposed to use complex potentials for writing the weld boundary conditions corresponding to the absence of displacements at their boundary. An example of a method of creating prestresses in the plate when welding a rectangular hole is given.

1. Introduction
The problem of determining the welding stresses in metal hull structures is relevant for various industries. Welding stresses and strains play an important role in ensuring the load capacity and durability of metal structures [1–4].

A considerable number of works [5–18] are devoted to the study of welding stresses. In [5], the effect of laser welding parameters of low carbon steel on the formation of X-shaped welds was investigated. Transient processes of laser welding were simulated on the basis of finite elements using the ANSYS software package intended for solving strength problems in various fields of engineering. Heat transfer processes in accordance with the geometry of the seam were simulated. Welding was characterized by a narrow zone of penetration of the weld into the base metal and the wide surface of the molten zone on the surface. Comparison of various options for the geometry of the weld showed that the welding parameters associated with changes in melt hydrodynamics are of great importance in the formation of welds in laser welding.

The study of welded joints of steel specimens that were performed using the process of arc welding of shielded metal and four different conditions of the welding material, which provide different levels of diffusible hydrogen in the weld metal, is described in [6]. The effect of diffusible hydrogen content on bending strength, critical stresses and tensile strength of steely welds under various electrode conditions was also determined. To study the effect of diffusive hydrogen on multi-path welding, the bend tests were performed. Residual stresses (axial stress and transverse stress) were also measured by recess drilling for various welding conditions of consumables. The maximum values of residual stresses in the center of the welding zone were determined for several cases that ranged from 218 MPa (12.43 ml/100 g of diffusion hydrogen) to 355 MPa (6.21 ml/100 g of diffusion hydrogen). Three-dimensional finite element simulation was performed to predict the distribution of residual stresses and the thermal profile along the welded joint.
The experimentally determined residual stresses correlated well with the values of the theoretically obtained residual stresses. It is shown that the content of diffusive hydrogen does not have a significant effect on residual stresses. Corrected residual stress values were also predicted taking into account the error caused by ductility. However, the bending characteristics of the welded joint were influenced by the content of diffusion hydrogen. The upper and main flexural strengths were measured, which is optimal for low content of diffusable hydrogen. Flexural strength values decreased with an increasing of diffusible hydrogen content.

In [7], friction stir welding was considered. It is a process in which objects are connected without reaching the melting point. This method is suitable for combining heterogeneous aluminum alloys. To experimentally measure the distribution of residual stresses in various zones of heterogeneous aluminum alloys, drilling technology was used in butt welding. The change in residual stresses in terms of thickness was also investigated. It was found that the maximum residual stresses are below the yield point of the material. It was revealed that the longitudinal residual stresses in the joint exceed greatly the transverse residual stresses. Vickers hardness tests were performed in the specimen profile, with the highest hardness values being observed in the contact zone.

2. Determination of welding stresses

2.1. Accepted hypotheses and assumption
Post-repair stress is determined by many factors. These are stresses from external forces acting on the repaired structure during the subsequent operation; technological stresses arising during the repair process and including welding stresses from external forces. With small sizes of zones of plastic deformations arising in the area of repair, the field of post-repair stresses is determined by the sum of the stress fields from all factors [19–20].

It is not possible to take into account all factors in the analytical calculation, therefore, we consider the most significant of them. These factors include residual welding stresses, external stresses acting on the structure in the area of repair.

2.2. Theoretical model
When welding a rectangular cutout, the residual welding stresses are calculated using the algorithm described in [11]. The solution of the flat elastic problem is used in the Kolosov-Muskhelishvili potentials about the stress state of a plate having a rectangular insert included into a plate with longitudinal and transverse interference (Fig. 1). Interference simulates the shrinkage of welds. The distribution of the displacement discontinuity along the insert edges is assumed to be linear. The accepted concept allowed us to develop a calculation algorithm, draw up a computer program for calculating welding stresses $\sigma_{x}$, $\sigma_{y}$ and $\tau_{xy}$ arising after welding a rectangular repair cutout.

![Figure 1](image.png)  
**Figure 1.** The design scheme for determining the optimal prestress: 1 – plate; 2 – rectangular cutout; 3 – centerline.
After welding the cutout and removing the prestresses, the stresses in the insert will be as follows:

\[
\begin{align*}
\sigma_{x1} &= \sigma_x - \sigma_p ; \\
\sigma_{y1} &= \sigma_y + k\sigma_p ,
\end{align*}
\]

where \( \sigma_p \) – external tensile prestresses acting along the axis \( X \); \( k \) – coefficient.

Assuming that the stress state of the insert is flat, we obtain the following expression for the potential energy of elastic deformation:

\[
\begin{align*}
u &= \frac{1}{2E} \int \int_S \left[ \left( \sigma_x^2 + \sigma_y^2 \right) - 2\mu \sigma_x \sigma_y + 2(1+\mu)\tau_{xy}^2 \right] dS^2 ,
\end{align*}
\]

where \( S \) – the area of the insert; \( \mu \) – Poisson’s ratio.

Using equation (1) we get:

\[
\begin{align*}
u &= \frac{1}{2E} \int \int_S \left\{ \left( \sigma_x^2 + \sigma_y^2 \right) - 2\mu \sigma_x \sigma_y + 2(1+\mu)\tau_{xy}^2 \\
&\quad + 2\sigma_p \left[ -\sigma_x + k\sigma_y + \mu(\sigma_y + k\sigma_x) \right] + \sigma_p^2 (1+k^2+2\mu k) \right\} dS^2 .
\end{align*}
\]

The minimum potential energy condition is written as \( u = du/d\sigma_p = 0 \).

From condition (4) using (3) we find the optimal external prestresses corresponding to the minimum potential energy:

\[
\sigma_p^{\text{min}} = \frac{\int \int_S \left[ \sigma_x - k\sigma_y - \mu(\sigma_y - k\sigma_x) \right] d^2S}{(1+k^2+2\mu)S} .
\]

Graphs for calculations \( \sigma_p^{\text{min}} \) according to (4) are given in Fig. 1 and 2 for restoring the strength of worn-out structures.

3. Method of solution

We choose the prestresses in the area of repair by the method of replacement. After removal of the prestresses the maximum technical efficiency of the repair will be ensured.

The main factors determining the technical efficiency of the repair are the total hull bending stresses, existing in the hull before welding the repair hole, and reactive welding stresses.

The repair holes include rectangular cutouts the dimensions of which do not exceed 0.25 of the main dimensions of the hull.

With large cutouts the reactive welding stresses are small and therefore one should strive to reduce the prestress from deformations of the hull structures being repaired.

In determining the optimal prestress the following must be known (Fig. 1): \( 2A \) – size of the long side of a rectangular repair cutout, m; \( 2B \) – the size of the short side of the rectangular repair cutout, m; \( \Delta \) – transverse shrinkage of the weld determined by appropriate methods or taken equal to the value of the average shrinkage \( \Delta_{sw} = 10 \text{ mm} \); \( C = A/B \) – the ratio of the sides of the repair cutout.

If a biaxial stress state arises when the bending moment is applied to the hull of the vessel in the repair area, the pressure ratio should be calculated:

\[
\beta = \sigma_{p1}/\sigma_{p2} ,
\]

where \( \sigma_{p1} \) – stresses acting perpendicular to the centerline, \( \sigma_{p2} \) – stresses acting parallel to the centerline.

To determine the optimal prestresses for the cutouts located along the centerline of the hull, the graphs shown in Fig. 2 were obtained. These graphs represent the dependence of the optimal
prestresses on the ratio of the sides of the rectangular cutout with a unit small side \( B_0 \), located along the centerline, with transverse shrinkage of the weld equal to its average value \( \Delta_m = 10 \text{ mm} \). Graphs are plotted for a range of values \( \beta_i \) from 0 to 0.3.

Figure 2. Dependence of optimal prestresses on the ratio of the sides of the rectangular cutout (the cutout is located along the centerline of the hull): 1 - \( \beta_i = 0.2 \); 2 - \( \beta_i = 0.1 \); 3 - \( \beta_i = 0.2 \); 4 - \( \beta_i = 0.3 \).

Figure 3. Dependence of optimal prestresses on the ratio of the sides of the rectangular cutout (the cutout is located along the centerline of the hull): 1 - \( \beta_i = 0.2 \); 2 - \( \beta_i = 0.1 \); 3 - \( \beta_i = 0.2 \); 4 - \( \beta_i = 0.3 \).

If the numerical value \( \beta \) coincides with one of the values \( \beta_i \), then the ordinate corresponding to the calculated value \( C \) is taken from the corresponding graph. The value of this ordinate is indicated by \( \sigma \).

If the calculated value \( \beta \) does not coincide with any of \( \beta_i \), then to determine \( \sigma \), the ordinates \( \sigma_1 \) and \( \sigma_2 \) are taken from two proximate graphs corresponding to values \( \beta_i \), equal to \( \beta_1 \) and \( \beta_2 \), such that \( k_1 < k < k_2 \). The ordinate \( \sigma \) is determined by the linear interpolation formula:

\[
\sigma = \left( \frac{\beta - \beta_1}{\beta_2 - \beta_1} \right) \sigma_1 + \sigma_2.
\]  

The optimal prestress is determined through the ordinate by the formula \( \sigma_p = \sigma (B_0A / B \Delta_m) \).  

If the transverse shrinkage \( \Delta \) is taken equal to the average shrinkage \( \Delta_m \), then the optimal prestress can be determined by the formula \( \sigma_p = \sigma (B_0 / B) \).

When determining the optimal stresses for the cutouts located perpendicular to the centerline of the vessel, it is necessary to use the graphs shown in Fig. 3. These graphs represent the dependence of the optimal prestress on the ratio of the sides of the rectangular cutout with a unit small side \( B_0 \), located...
perpendicular to the centerline, with transverse shrinkage of the weld, equal to its average value \( \Delta_m = 10 \text{ mm} \). Graphs are presented for a range of values \( \beta_i \) from 0 to 0.3.

The calculation of optimal stresses for cutouts located perpendicular to the centerline is carried out in the same way as for the parallel plane of cutouts. The data is taken from the graphs shown in Fig. 2. The sequence of welding holes is as follows: one long side of the rectangular cutout is welded first, then the other, then the short sides are successively welded. Welding is performed by the back-step method.

4. Conclusion
The presented method allows you to determine in advance the field of prestress in the hull structure with a rectangular cutout which later, after welding the cutout, will allow one to neutralize the residual stresses in the welding zone. We consider the repair holes, the dimensions of which do not exceed 0.25 of hull basic dimensions.

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