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Numerical investigation of residual thermal stresses in welded joints of heterogeneous steels with account of technological features of multi-pass welding

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The paper describes a two-dimensional mathematical model to evaluate stresses in welded joints formed in multi-pass welding of multi-layered steels. The model is based on a system of equations that includes the Lagrange's variational equation of the incremental theory of plasticity and the Biot's variational principle for heat transfer simulation. In the constitutive equations, the changes in the volume which occur as a result of phase transitions can be taken into account. Therefore, the prehistory and impact of thermal processing of materials on macroscopic properties of the medium can be considered.

The variational-difference method is used to solve both the heat transfer equation for calculation of the non stationary temperature field and the quasi-static problem of thermoplasticity at each time-step. The two-dimensional problems were solved to estimate the residual thermal stresses (for the case of plane stress or plane strain) during cooling of welds and assessing their impact on strain localization in the heat-affected zone under tensile and compressive loading considering differences in mechanical properties of welded materials.

It is shown that at initial stages of the plastic flow, the residual stresses significantly affect the processes of stress concentration and localization of strains in welded joints. To estimate the model parameters and to verify the modeling results, the available experimental data from scientific literature obtained on the basis of the Satoh test for different welding alloys was used.

1. Introduction

The technology of fusion welding is widely used in manufacturing steel structures for various purposes. In addition to apparent benefits, the compounds obtained in this way have a number of features the significance of which becomes clearer due to active development of physical mesomechanics of materials [1,2]. These features include, as an example, a multifractal structure of welded materials, nonlinearity and multilevel distributions of internal stress concentrators, heterogeneity of chemical composition in the welded material volume. Application of the physical mesomechanics approach to study the deformation processes in welded joints allows establishing the basic reasons for which, in most cases, the weldments are

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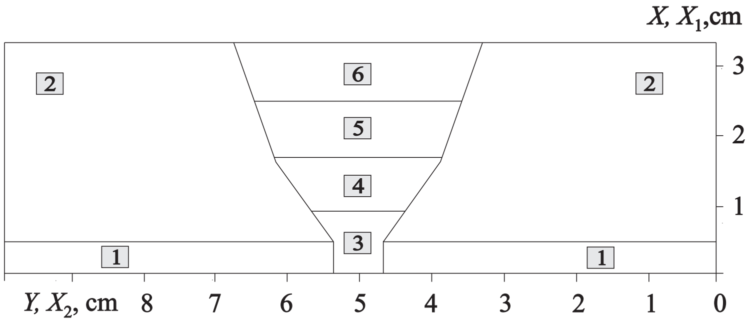

Fig. 1. Scheme of the welded joint: 1 is protective layer; 2 is base metal; 3, 4, 5 and 6 are successively created layers in the multi-pass weld, $X=X_1$ and $Y=X_2$ are Lagrange orthogonal coordinates.

destroyed in the weld zone [3,4]. The computer vision methods [5], specially designed for this purpose, allow establishing the impact of material mesostructure on its behavior and fracturing under loading.

A significant impact of internal interfaces on behavior of the loaded material is theoretically investigated, for example, in [6]. Viewed in this way, identification of the causes for formation of one or another structure of the weld and the heat affected zone is considered to be of current importance. As a result of the investigation described in [7], on the basis of numerical modeling of thermal processes in the weld pool, it was found that the pulsed power supply with a linearly increasing rate of the heat source contributes to formation of a more homogeneous internal structures that is confirmed experimentally. Among numerous factors to determine the strength of welded joints, the residual stresses evolved during cooling of the weld material and its environs are of significant importance. As a rule, the welded joint is formed during fusion welding as result of sequential filling of the multi-pass weld with the melted electrode material with a fairly significant time intervals between successive instants of layer formation. Depending on these factors, heterogeneous and non stationary temperature fields generate heterogeneous residual stress and strain, which can be regarded as a relatively independent factor for formation of the internal structure that impacts the weld strength.

An actual problem is the development of the models that can be used to get a realistic representation of the distribution of residual stresses for multi-pass welds. A numerical method proposed in this paper allows modeling of quasi-static processes of stress concentration and strain localization during multi-pass welding and successive mechanical loading of the weld. The constitutive equations of the model are defined for a wide range of temperatures. The numerical program was developed for 2D simulations and on this basis, the stress–strain parameters were calculated for the model samples. The obtained values correspond to the experimental data that confirms the accuracy of model representations. The calculations were carried out for the case of *V*-shaped edge preparation of welds in low alloy steel with the surface layer from high-alloy steel and metal electrodes with varying degrees of alloying.

2. Problem statement and calculation method

Among various features of welding technology to be considered when calculating residual stresses one can distinguish the following: the original shape of weld edges, difference in physical and mechanical properties of welded materials and electrode material (welding wire), an inhomogeneous temperature field which depends on the speed of weld layer welding and also on the instant of time of layer formation in multi-pass welding. In addition, an essential feature of the welding process is the fact that the temperature of the weld from the instant of time of its formation till the start of its exploitation varies in a wide range from about 273 K to 1800 K. Therefore, the impact of phase transitions in the material during its cooling is to be considered.

The method proposed for solution of the thermoplasticity problem applied to the problems of the thermal stress calculation allows us to investigate the impact of these factors on the distribution of residual stresses in welds and to consider the impact of residual thermal stresses on the properties of the weld under succeeding mechanical loads.

The main features of the proposed mathematical model can be considered for calculation of residual stresses in the welded joint in steel 09G2C with a protection layer from steel 08Cr18Ni10Ti. Fig. 1 shows the scheme for the modeled hereinafter sample with the base metal (steel 09G2C) thickness $L_1^1 = 28\,\text{mm}$ and the coating metal (steel 08Cr18Ni10Ti) thickness $L_1^2 = 4\,\text{mm}$ and length $L_2 = 100\,\text{mm}$.

For samples of this type, the initial edge preparation of the weld with a *V*-shaped form, discussed below, is often used (Fig. 1). The process was simulated for sequential filling of the weld with molten metal within four passes of the electrode. Layer 3 was filled at the initial instant of time $t = 0\,\text{s}$. The time delay between the overlay of layers 3, 4, 5 and 6, (Fig. 1) was set equal to 6 s. One of the features of the described solution is modeling of variation of the temperature field and stress–strain state in the sample with changing geometry during filling of the weld with the melted electrode metal. The air was assumed as external environment for formulation of boundary conditions required to solve the heat transfer equations.