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Reducing deformations in thin-sheet high-strength steel structures based on *CAE*-analysis of welded joints

High competition in the field of mechanical engineering requires the manufacture of lightweight thin-sheet structures made of high-strength steels, ensuring the geometry of certain accuracy. It is possible to ensure the given geometry by improving the residual deformation reduction measures. Based on the analysis of clamping rigidity influence on the stress-strain state of an assembly, the deformation reduction has been investigated by means of computer simulation by finite element method. A clamping model was obtained, which makes it possible to regulate the level of residual stresses and deformations confirmed experimentally.

Keywords: welding process simulation, stress-strain state, high-strength steels, welding fixture, finite element method.

Introduction

Welding of thin-sheet parts from martensitic-bainitic steels (panels, beams, shells) is accompanied by the post-welding assembly geometry changes. This is due to the structure stability loss caused by small thickness of the parts and the resulting stresses in welded joints on account of thermal loading of the parts with the welding arc and structural conversions accompanied by a change in the volume of the structure produced. Wide-spread methods to reduce the deformation are the use of welding fixtures, selection of assembly sequence ensuring maximum structure rigidity, and application of negative deflection.

The welding fixture rigidly fixes the parts during welding, which results in accumulation of residual stresses in the weld and heat-affected zone. When the critical value is attained, cracks appear in the welded joint. Therefore a new fixation scheme is proposed. During welding the clamp changes its rigidity, which results in potential deformation of the parts reducing the residual stress level. As a result, the clamp is adapted to residual stress distribution during welding. The adaptive clamp may be implemented in pneumatic, hydraulic, and mechanical welding devices. Let us consider the influence of adaptive clamps on the shell stress-strain state (SSS).

Generation and distribution of stresses and deformations in the longitudinal single-run welds of cylindrical shells, when they are welded and fixed in fixtures, have no fundamental differences from butt welding of two sheets [1, 2]. This simplification was also used in [3], where the SSS after longitudinal welding of a tank vessel was also studied as exemplified by two plates.

During the welding process simulation, the adaptive clamping force was searched for, thanks to which the post-welding part surface deformation level in the cross-section in question will be the least and the residual stress value increase will be minor to avoid potential crack formation.

Methods and materials

Simulation of a welding process was accomplished with a shell, in which a longitudinal weld was made by argon-arc welding using a non-consumable electrode (Fig. 1).

High-strength 30KhGSA steel was used as the base and welding material.

The thermomechanical problem was solved relative to the weld stresses and deformations for the butt joint on 100×100×3 mm plates.

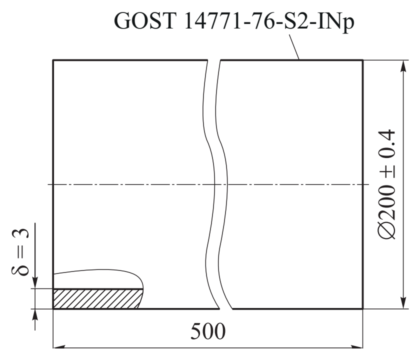

Fig. 1. Article sketch

The sketch of the model in question is provided in Fig. 2.

Due to a single-run plate welding, the case was considered with plate heating using a linear heat source, when the temperature over the sheet (δ) thickness may be assumed equalized.

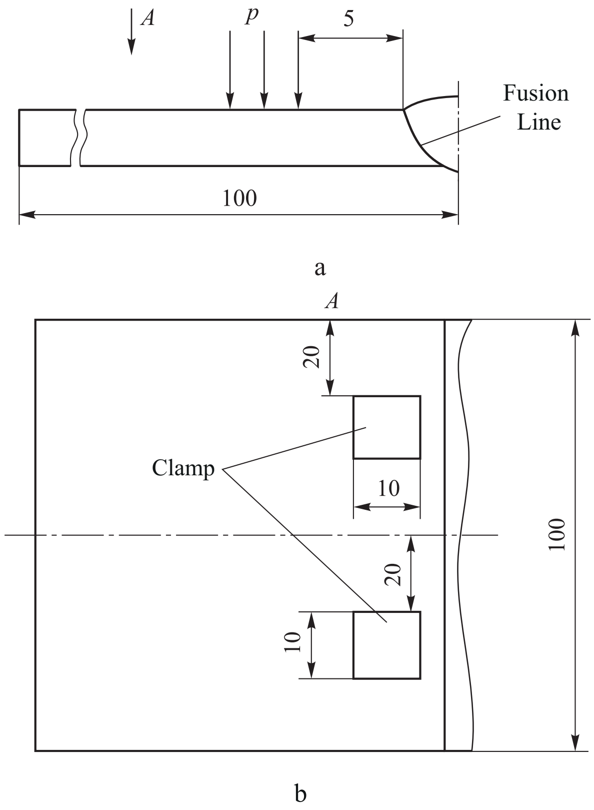

Fig. 2. Sketch of the model in question

The boundary conditions are set as thermal interaction with the ambient air at 20 °C and without air motion.

The calculations were performed in *SYSWELD* Software Package. To solve the thermal and mechanical problem 3D prismatic-shape elements were used, which in aggregate make up a computational mesh (Fig. 3). In the weld area and heat-affected zone (HAZ) the computational mesh was condensed relative to the others due to significant thermal and mechanical field gradients.

Software implementation of the clamp consists in the following. In the pressed state during welding the parts will start moving, which limits the clamping force in the contact areas. Consequently, the physical clamp can be removed from the model but at the same time it is necessary to increase rigidity of the parts in the fixation areas. The clamping force is calculated in kilonewtons, therefore, the effect of the friction force between the part and the welding table on the part deformation pattern increases during the welding process. The friction force increases the part surface rigidity opposite to the fixation areas. The replacement enables model simplification, which, in its turn, will reduce the mechanical calculation complexity and computer hardware requirements.

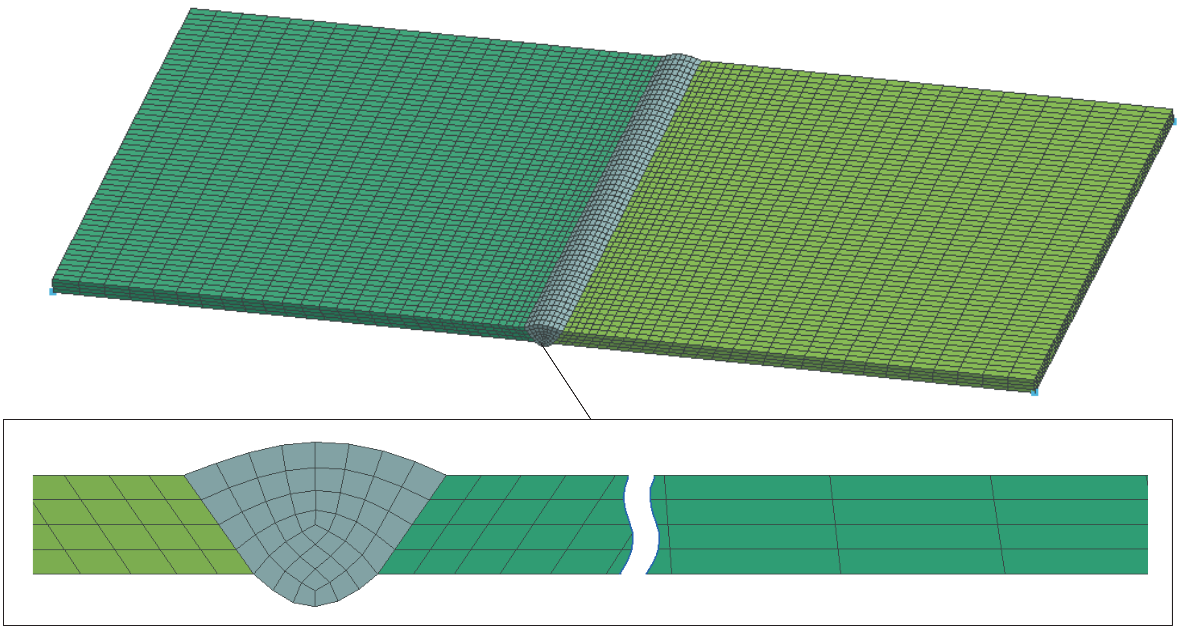

Fig. 3. Mesh for thermal and mechanical problem solution

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The loading pattern includes the force from the thermal load and four adaptive clamps. In the model the fixation areas are implemented by four flat clamping action areas P = 0…5000 N, in which the rigidity is increased in accordance with the clamping force. The force of 0 N corresponds to free movements, whereas 5000 N implies that the heat expansion effect will be insufficient to overcome the clamping action, and, consequently, the fixation may be considered rigid. On the opposite side of the plate, at the same distance from the weld butt, areas of increased action of the friction force were identified.

The friction force was determined by the following formula [4]

$$F_{\text{тр}} = \mu N, \quad (1)$$

where $\propto$ – static friction coefficient, $\mu = 0,2$ [4];

N – normal force acting opposite to the clamp compression.

Due to the fact that the structure weight is negligible compared with the compression force, it may be disregarded, $N = P$. The input values of P and $F_{\text{тр}}$ are provided in the table.

Input values P and $F_{\text{тр}}$

External loads, N	Values					
P	600	1200	1800	2400	3000	5000
$F_{\text{тр}}$	120	240	360	480	600	1000

30KhGSA steel is a typical martensitic-bainitic grade in which austenite is converted into martensite and its component structures after welding [5]. In its turn, the effect of the phase (structural) conversions on the residual stresses and deformations during welding is so significant that their assessment without account for the structural transformations results in major errors. This effect is due to the change in the volume and properties of the metal during transformation. Martensite transformation is accompanied by the metal volume increase by approximately 3 % and substantially changes the kinetics of the deformations and stresses [6]. It follows that the plate SSS should be studied together with the produced structure after welding. And it will result in the increase of complexity of the clamp rigidity analysis. Therefore, it was decided to perform the calculation, where for the material considered *SYSWELD* Software used a kinetic diagram of continuous cooling but during the SSS analysis the finite structure is not considered, as it is linked to rate of energy input determining the ratio of the structures in the plate.

Based on the work conducted the clamp rigidity effect on the plate SSS at the rate of energy input of 500 J/mm was experimentally verified. Welding was performed in the following modes: $I_{\text{св}}$ = 120 A, $U_{\text{д}}$ = 11.9 V, $V_{\text{св}}$ = 2 mm/s. To provide equal conditions and constancy of all the parameters, welding of three samples was conducted using a welding column. It enabled excluding the probability of an accidental error due to the human factor because the welder’s skills were excluded from the experiment. The selected mode to the maximum extent coincided with the series of experiments in which the rate of energy input was equal to 500 J/mm. Three specimens (six plates) of 3-mm thick high-strength 30KhGSA steel were welded. Three cases were checked: welding in the free state, with the varying clamp rigidity, and in the welding fixtures ensuring rigid plate fixation during welding. High-strength steels are sensitive to the cooling rate and even in case of its minor variation the steel structure will be completely different. Further study of such plates is not admissible. To ensure equal conditions for all the specimens and to reduce the possibility of obtaining different structures, asbestos sheet was laid under the plates and clamps during the experiment.

20 kg (or approximately 200 N) loads installed on each plate simulated the clamping ensuring constant pressure on the part. For the approximate assessment of the residual stress level, static bend and elongation tests in accordance with GOST 6996–66 were selected. Based on the test

results it is possible to determine the weld and HAZ plasticity and strength.

Results

Based on the solution of the thermomechanical problem maximum stresses and deformations as a function of the set force were determined (see Fig. 4). The data analysis revealed that there is such a critical force value $P_{кр}$, at which the maximum deformation area changes its localization. Graphs in Fig. 4 show that the least deformations are observed at the force of 600 N, when residual deformations were reduced by 45 % as compared with the case of free state welding whereas the stresses increased by only 3 %.

The mechanical tests showed that in case of free state welding the weld joint strength and plasticity were increased as compared with the rigid fixation. This is presumably due to the favourable condition of the weld metal crystallization. The weld joint tensile strength using the clamp was increased by 67 %, bend angle – by 20 %, as compared with the rigid fixation.

X-ray inspection demonstrated the absence of cracks in the welded joints, i. e., the stress level did not reach the ultimate strength in any of the cases. Deformations in case of free-state welding amounted to 0.55 mm, using the clamp – 0.45 mm, with the rigid fixation – 0.4 mm. The difference

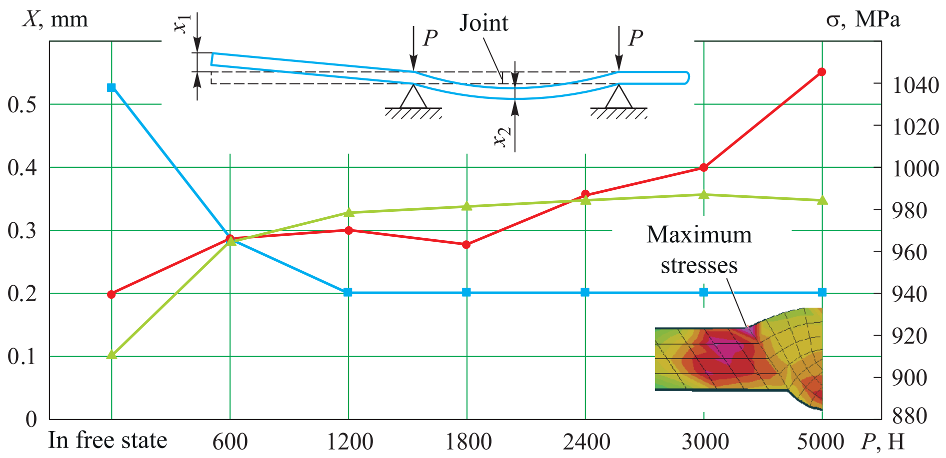

Fig. 4. Change of the maximum residual stresses and deformations as a function of P: — deformations $X1$; — deformations $X2$; — stresses

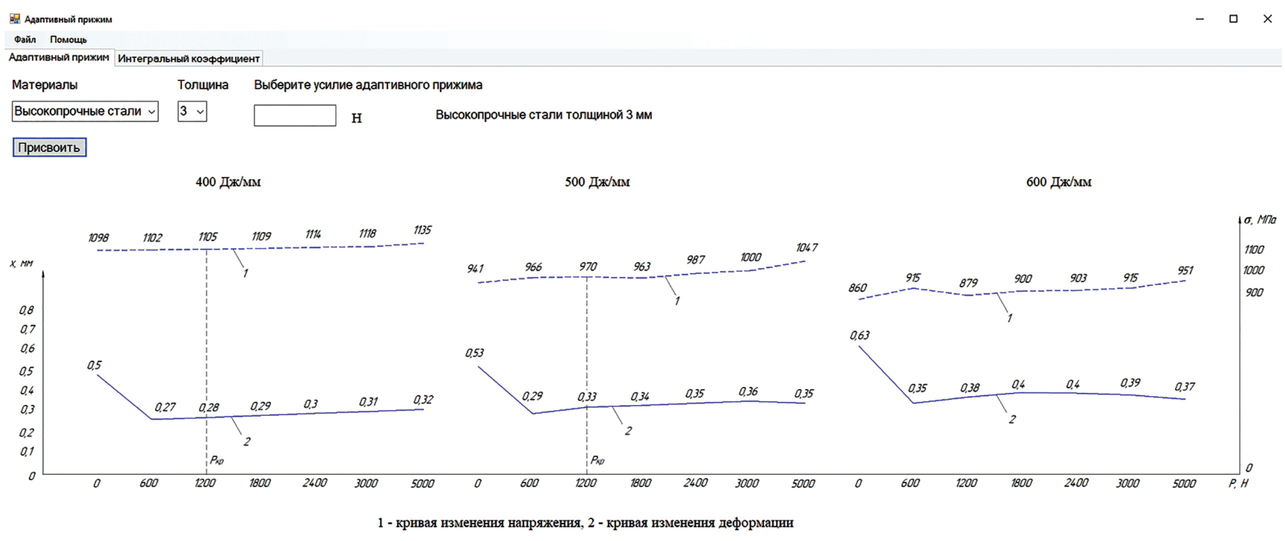

Fig. 5. Graphical visualization of the software module

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in the calculated and experimental data did not exceed 11 %.

The results obtained expanded the software module library, the graphical component is provided in Fig. 5, in which the methodology is implemented to select the clamping force depending on the rate of energy input and thickness of the parts to be welded. Currently, the module library includes the results on such wide-spread materials as high-strength steels, aluminium and titanium alloys with the thickness of 1, 2 and 3 mm. The software enables to select the force and creates the clamping model readable by the *CAE*-platform. The module will be integrated into *ProWeld* software package.

Practical application of the study results

Based on the work completed, it was proposed to equip the welding fixtures with variable rigidity clamps, as per Fig. 6.

The variable rigidity clamps in the welding accessories ensure feedback alignment of the clamp elasticity and stress level in the welded joint within the value range close to the ultimate strength. It enables reducing the impact on the welded piece during welding, which effectively reduces the deformation level and the probability of hot cracking. It is meant that, if the piece starts counteracting the clamp due to thermal expansion with the force exceeding the preset value, the clamp ensures a certain travel for article deformation. It enables relaxing the stresses in the welded joints and heat-affected zone and limit the part deformation during welding. For example, a check valve installed in a pneumatic clamp enables reducing the air pressure in the sleeve, thus reducing the force exerted on the part during welding. The piece is deformed relaxing residual stresses. And when elastic deformations disappear, the pressure in the pneumatic clamp sleeve increases becoming equal with the supply system pressure. This arrangement ensures impact on the part with a certain force which does not change with time.

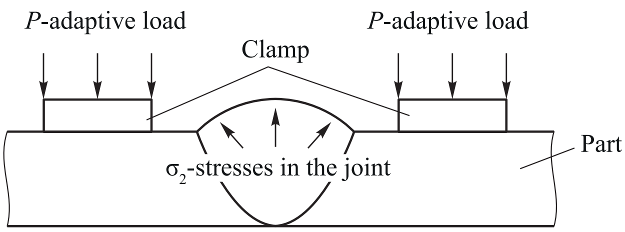

Fig. 6. Adaptive clamp

The results obtained may be used for the calculation of two plates in case of butt welding and in case of a longitudinal joint in the shell.

Conclusion

A model of deformation of a high-strength steel thin-sheet part during welding was developed by means of computer-aided calculations in *SYSWELD* package.

The differences between the calculations and experimental data did not exceed 11 %.

Experimental verification of the adaptive clamp influence on the plate SSS demonstrated a similar deformation value and the absence of cracks in the X-ray images points out that residual stresses in the plates are lower than the ultimate strength.

Based on the calculation results the plate deformation by 45 % in case of variable-rigidity clamp was identified; besides, residual stresses insignificantly increased and made up 3 %. The cracking probability is supposed to remain at the same level.

According to the data obtained it is possible to determine the residual stress and deformation level, both in case of the plate butt-weld joint and in case of a longitudinal joint of the shell.

The work results expanded the library of the developed software module on the clamp force selection.

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Снижение деформаций в тонколистовых конструкциях из высокопрочных сталей на основе *CAE*-анализа сварных соединений

Высокая конкуренция в области машиностроения требует изготовления облегченных тонколистовых конструкции из высокопрочных сталей с обеспечением геометрии определенной точности. Обеспечение заданной геометрии достижимо при совершенствовании мер снижения остаточных деформаций. Исследовано снижение деформации на основе анализа влияния жесткости прижима на напряженно-деформированное состояние сборки с помощью компьютерного моделирования методом конечных элементов. Получена модель прижима, позволяющая регулировать уровень остаточных напряжений и деформаций, подтвержденных экспериментальным путем.

Ключевые слова: моделирование процесса сварки, напряженно-деформированное состояние, высокопрочные стали, сварочное приспособление, метод конечных элементов.

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