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Quality increase for single-welded joints of thin-walled structures by means of simulation modelling

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ABSTRACT: The Simulation calculation module and the SolidWorks software package have helped to define the optimal shape and dimensions of single-welded joints which may serve the basis for calculating the process parameters of welding. Having compared the models with different weld cross-sections the authors have defined that the weld height and width do not significantly affect the stress concentration, and the stress concentration and value mainly depend on the shape of the root bead and the gap size between the welded parts.

KEYWORDS: Weld modeling; Welding thin-walled structures

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RESUMEN: *Aumento de calidad en uniones soldadas de estructuras de paredes delgadas mediante modelo de simulación*. El módulo de cálculo de simulación y el paquete de software solidworks han ayudado a definir la forma y las dimensiones óptimas de uniones soldadas simples que pueden servir de base para calcular los parámetros de proceso de soldadura. Habiendo comparado los modelos con diferentes secciones transversales de soldadura, el autor ha determinado que la altura y el ancho de la soldadura no afectan significativamente la concentración de tensión, y la concentración y el valor de la tensión dependen principalmente de la forma del latido de la raíz y del punto de separación entre las partes soldadas.

PALABRAS CLAVE: Modelado de soldadura; Soldadura de estructuras de paredes delgadas

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1. INTRODUCTION

The increasing prices for metal prompt the use of thin-walled metal profiles (pipes, shaped pipes, roll-formed sections) for the manufacturing of welded structures.

Due to its versatility, relative simplicity of process mechanization and automation the consumable-electrode arc welding in shielding gases is one of the most widely used welding methods in the production of welded structures (GouMing *et al.*, 2003). Despite the prevalence of the method, it is often problematic to ensure the required quality of welded joints during arc welding in shielding gases, namely because of the appearance of defects (Mochizuki *et al.*, 2007).

According to its economic and operational characteristics, the use of single welded joints with free weld formation (without backing) is the most advantageous, and sometimes the only possible, method for welding thin-walled materials. Such joints are easy to perform and less labour-intensive, since they do not create difficulties in welding preparation in the form of machining the edges of irregular shape and the need for two-side welding, they also reduce the likelihood of decreasing the performance characteristics of the welded joint and metal structure in general.

The main disadvantage of single-welded joints is the low stability of qualitative weld formation, while its shape and dimensions are very important, and the efficient formation of weld and the absence of defects define the reliability and quality of the whole welded joint.

Therefore, in most cases preference is given to more expensive and constructively complex welded joints with the so-called "guaranteed penetration". Such connections include two-side welded joints, joints with backing run of weld root, joints with forced root formation on the back-up plate (non-removable or removable), lap joint, etc. The disadvantages of these joints are the need to use additional engineering elements (back-up plates), the increase in mental consumption of the structure and labor intensity of assembly and welding operations, the complication of the welded joints structure and the technological process of welding. In most cases the use of different types of back-up plates and inserts significantly impairs the performance of welded joints, creates the conditions for crack formation in them and reduces the effective cross section of structures. Quite often, gapping or mismatching of edges, welded to the back-up plates, significantly changes the conditions of heat removal from the welded joint and causes the emergence of defects in the welded joints.

Thus, ensuring the formation of a high-quality and stable single-rim weld in single-welded joints will help to eliminate a number of restrictions on their use in welded structures. This will allow to use the joints of simpler design, which do not require great additional labour costs, and, consequently, reduce labour intensity and cost of work and ensure the high quality of the joint.

2. LITERATURE REVIEW

The main problem in welding thin-walled structures is the formation of burn-through caused by the geometric deviations of the position of welded edges. The shape and dimensions of the weld when welding thin-walled materials depend on many factors, the most important among which are the fusion zone width and the amount of weld deposit (Zasyad'ko and Korinecy, 2010).

An important aspect of welding thin-walled materials is the preparation of parts to be welded, namely such parameters as gap size and edge alignment (Murakawa *et al.*, 2012). In case of welding thin-walled structures there appear the so-called welding stresses and deformations, which are caused by longitudinal and transverse thermal contractions and depend directly on the gap size between welded edges. The paper (Soul and Hamdy, 2012) proposes the methods for reducing the residual welding stresses by means of affecting the temperature field by water cooling and laser heating. A rather effective method of reducing residual stresses is also an optimal welding sequence (Romeo-Hdz. *et al.*, 2016).

The influence of weld sizes and preparation on the values of stresses and deformations is often ignored when designing and producing the structures because of the lack of quick and inexpensive estimation methods (Guoqing *et al.*, 2014).

2.1. Research purpose and objectives

The purpose of the paper is to improve the quality of single-welded joints by means of matching the parameters of edge preparation and pre-welding assembly with the geometric characteristics of the obtained weld.

In order to achieve the set purpose, we propose to study the effect of edge preparation and assembly on the values of equivalent stresses when applying the tensile load by means of simulation modelling and using the known CAD, CAE systems. The method of simulation modelling helps not only to define the effect of stresses, but also the most optimal parameters by means of parameter optimization (Islam *et al.*, 2014).

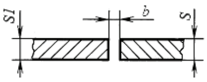
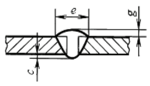
2.2 Research methods and materials

To study the influence of welding parameters on the geometrical dimensions of the weld, a low-alloy steel sheet, 3.0 mm thick, was chosen, as it is most often used for manufacturing welded structures.

The dimensions of welded joint and weld for the thickness of 3.0 mm, in case of welding in the environment of shielding gases, are defined by the regulatory document GOST 14771-76, which is currently in force in Ukraine. The dimensions of welded joint and weld for the thickness of 3.0 mm, according to this standard, are shown in Table 1.

The controlled dimensions of the weld (Table 1) are the weld width *e*, the height of weld reinforcement *g* and root bead *c*.

Table 1. Structural components and dimensions of the welded joint

Symbol legend Welded joint	Structural components and dimensions		$S=S_1$ *mm*	Dimensions, *mm*						
	of the prepared edges of the parts to be welded	of the weld		*B*		*E*	*G*		*C*	
				Nominal value	Tolerance	Not exceeding	Nominal value	Tolerance	Nominal value	Tolerance
C2			3.0	0	+1.5	8	1.5	±0.5	1.5	±1.0

3. WELD MODELING TECHNIQUE

In CAD programs, welds are usually modeled as small-size solid objects in the cross section. In this case the nodes of the finite element mesh on the contact surfaces of welds and welded parts must coincide.

The computation technique of the welded structures by means of the programs and finite-element method (FEM) is the following:

- development of the model geometry of welds and welded parts;
- selection of the type of finite elements;
- development of elastic constants and physical-mechanical properties of materials;
- development of the finite element mesh (setting element dimensions in the area of welds and outside it; decomposition of weld parts into finite elements; joining the mesh nodes on the contact facets of welds and welded parts);
- setting boundary conditions, loads and performing strength analysis.

In the computation of welded joints, the following preparation variants of their finite-element model can be used:

- single body model;
- gapped body model;
- midsurface model.

The variant of the midsurface model is the most suitable for thin-walled welded structures. In this case, it is possible to replace solid finite elements with plane finite elements, which reduces the computation time.

The results obtained by computing the stresses should be compared with the constants, characterizing the strength. For welded joints, the best approach is to compare the calculation data of simple models with the experiment results, which makes it possible to determine the necessary corrections and apply them to real structures. In this paper the SolidWorks software package with the Simulation calculation module was used to model and calculate the geometrical dimensions of the weld to analyze the performance of joints.

The most difficult and time-consuming stage of data preparation is the geometric model development. The finite element mesh is applied to the developed model. The specific feature of the mesh of the welded joint is its densification in the areas of greater stress concentrations, on weld surface and on the contact facets of the weld and joined parts. The developed model of welded joint with the applied mesh is shown in Fig. 1.

The elastic-plastic properties of the joined materials and the weld material were taken into account, in particular the modulus of elasticity, the Poisson's ratio, yield strength and material strength.

The boundary conditions, given in the calculation model, simulate the real conditions of fixing and loading of the specimen.

At the model nodes, corresponding to the surface of the specimen, zero degrees of mobility were set along the *Y* and *Z* axes and the power load *F* was distributed along the *X* axis. The calculations with the use of the obtained finite element model concerned the calculation of the unknown nodal displacements and stresses. The displacements were calculated according to the following matrix Eq. (1):

$$[K].\{u\} = \{F\}, \tag{1}$$

where $[K] = \sum_{i=1}^{N} [K_e]$ - global stiffness matrix;

$[K]$- stiffness matrix of a single element; N- total number of finite elements in the model;
$\{u\}$- vector of nodal displacements; $\{F\}$- real load vector.

Stresses were calculated according to the following Eq. (2):

$$\{\sigma\} = [K].\{\varepsilon\}, \tag{2}$$

where $\{\sigma\}$- stress vector; $\{\varepsilon\}$- vector of relative deformations.

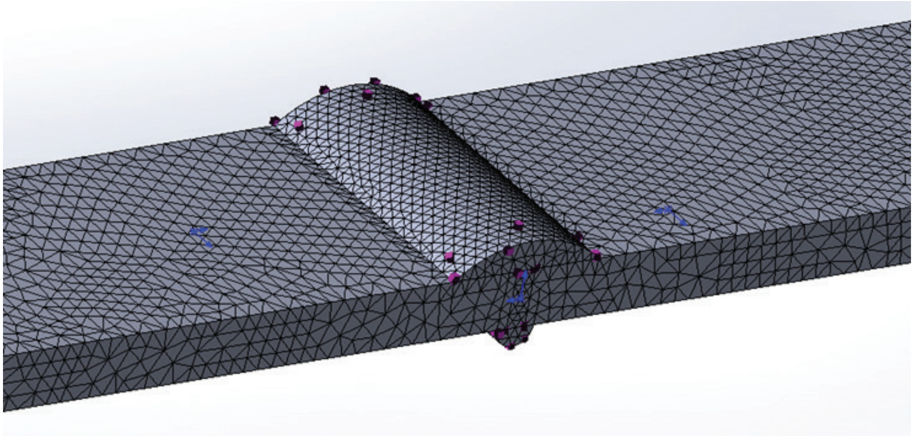


FIGURE 1. 3D model of the welded joint with the finite element mesh.

3.1. Results of simulation and optimization of weld geometrical dimensions by means of finite element method

The values and nature of welding stresses and deformations are defined by a set of technological and design factors. The values and nature of stresses and deformations during welding are most strongly influenced by the degree of heat concentration, which depends mainly on the welding method and conditions. However, the shape and dimensions of the weld will also have a significant effect.

The weld shape is defined by the following parameters:

- *e* – weld width;
- *g* – weld height;
- *c* – root bead height.

It is known that according to the regulatory documents these dimensions have certain tolerances that can significantly affect the values of stresses and deformations during welding.

Having modeled the specimen of the welded joint with minimum and maximum tolerances of the main weld dimensions we defined the Von Mises equivalent stresses distribution. The nature of the equivalent stresses distribution for the weld with maximum and minimum tolerances of its dimensions is shown in Fig. 2 and Fig. 3 respectively.

4. RESULTS AND DISCUSSION

The analysis of stress distribution diagrams showed that the highest concentration of critical stresses in the welds, both with larger and smaller cross-sectional areas, would be in the transition area

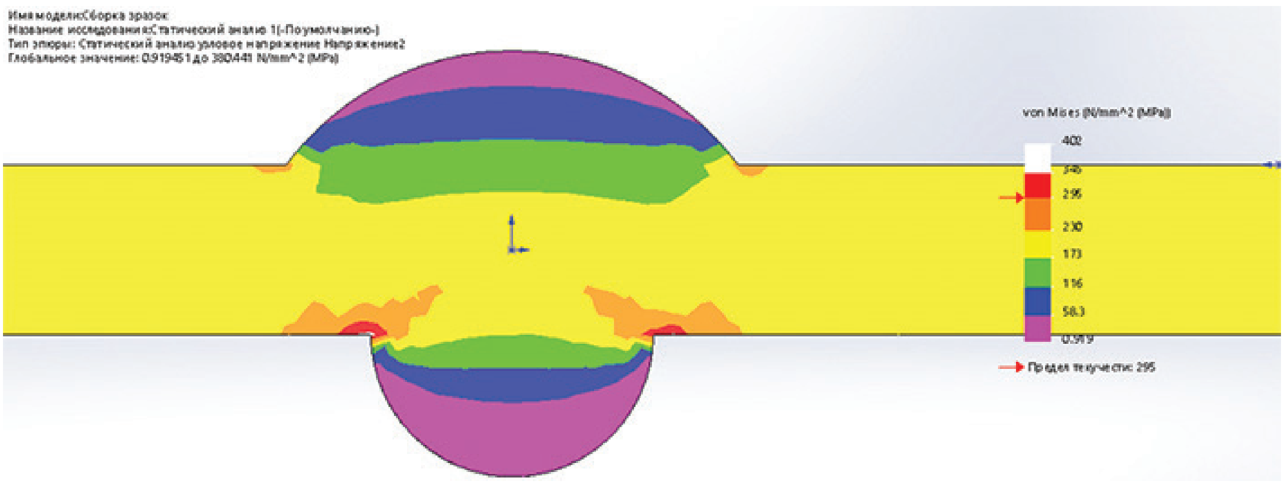


FIGURE 2. Fields of equivalent stresses for the weld with maximum cross section.

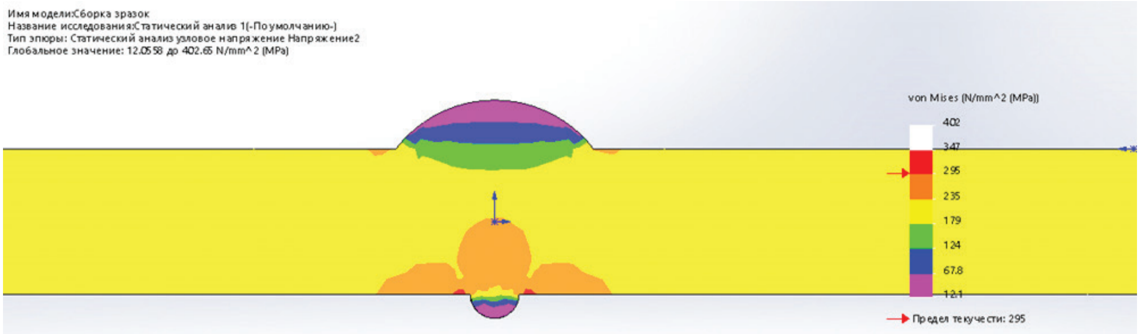


FIGURE 3. Fields of equivalent stresses for the weld with minimum cross section.

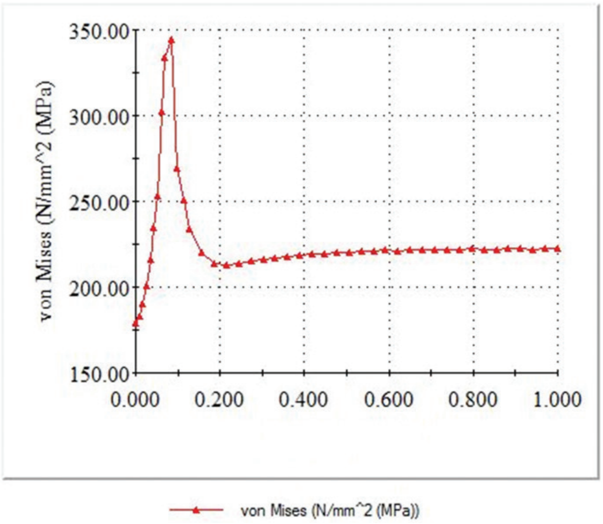


FIGURE 4. Von Mises equivalent stresses distribution along the lower edge of the weld with the maximum cross sectional area.

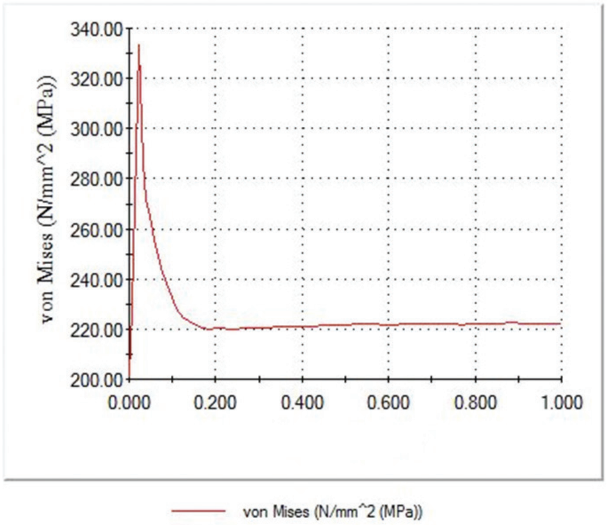


FIGURE 5. Von Mises equivalent stresses distribution along the lower edge of the weld with the minimum cross sectional area.

from the weld to the base metal, both on the part of weld reinforcement and on the part of root bead. Besides, stress increases in the inner part of the root bead and weld with a smaller cross section, and decreases in weld reinforcement metal.

The comparison of the models with smaller and larger cross-sections of the weld shows that the weld height and width do not significantly affect the stress concentration. The concentration and values of stresses mainly depend on the shape of root bead and the gap size between the welded parts. The stress jump in the transition area can be also observed in the equivalent stress distribution diagrams along the lower edge of the cross section of welded joints (Fig. 4 and Fig. 5).

The diagrams (Fig. 4 and Fig. 5) show that reducing the dimensions of the root bead and the gap between the parts results in decreasing the value of equivalent stresses in concentration areas by 4%. However, at the same time, in addition to the concentration of stresses in the transition area the growth of equivalent stresses can be observed inside the weld on the side of the root bead (Fig. 3). Besides, on the joints models with maximum and minimum cross-sections there is stress concentration, the value of which approaches the yield strength in the transition area between weld reinforcement and base metal.

It can be seen that the distribution nature and values of equivalent stresses in the joint depend mainly on the shape and dimensions of the root bead.

Therefore, the next stage of our research was to define the optimal weld parameters in order to minimize equivalent stresses. The Simulation calculation module of the SolidWorks software package helps to optimize the design. By setting the main criteria and optimization the goals, the program defines the most optimal option.

The optimization criteria in our research were the main geometrical dimensions of the weld (weld

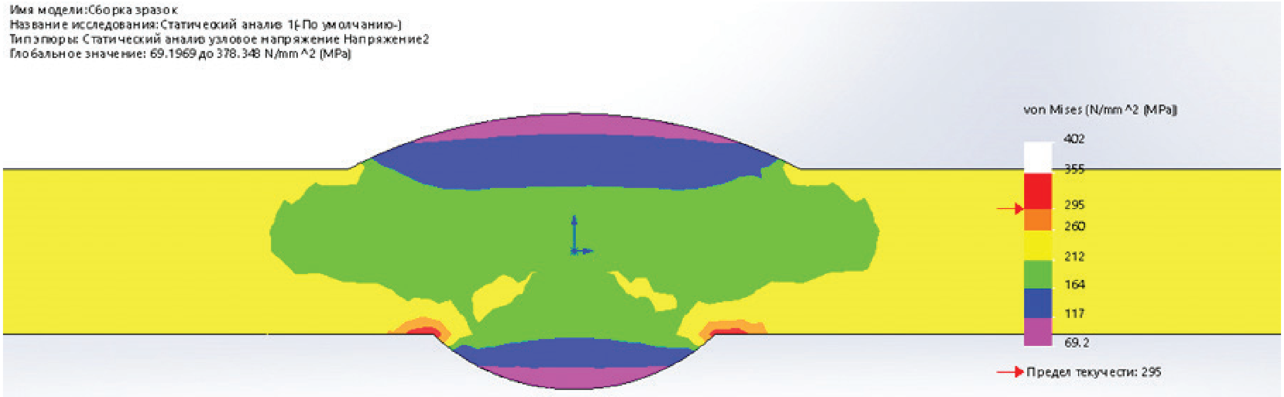


FIGURE 6. Fields of equivalent stresses in the optimized weld.

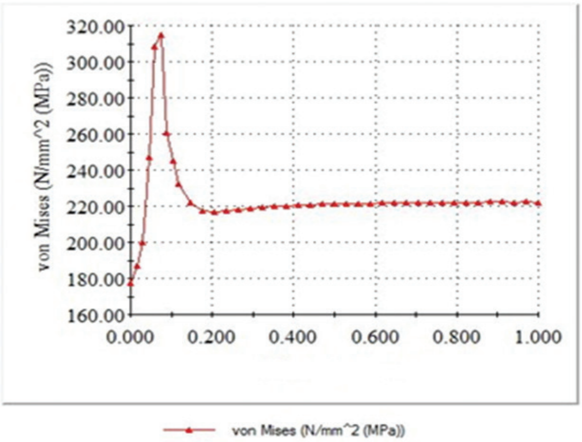


FIGURE 7. Von Mises equivalent stresses distribution along the lower edge of the optimized weld.

width and height, gap size between the welded parts as well as the root bead width and height), and the main objective was to minimize the stresses that exceed the metal yield strength.

Having performed the optimization computation, the optimal shape and dimensions of the weld were determined. The results of the optimized model are shown in Fig. 6, and the distribution of equivalent stresses – in Fig. 7.

The optimized shape of the weld shows that an increase in the width of the root bead can significantly reduce the concentration of stresses in the transition area of the face and back of the weld as well as inside the root bead.

The equivalent stress distribution diagrams (Fig.7) show that the values of stresses decreased in their concentration area. The values of stresses decreased by 10%, compared with the weld with maximum cross-section, and by 5%, compared with the weld with minimum cross-section.

TABLE 2. Geometrical dimensions of welds

Weld cross section	Gap, mm	Weld width, mm	Weld height, mm	Root bead width, mm	Root bead height, mm
Maximum	3,0	8	2	2.5	2.5
Minimum	0,1	5	1	0.5	0.5
Optimal	2	7	1	2.0	1

Table 2 shows the calculated minimum, maximum and optimal cross sections and the geometrical dimensions of the investigated welds.

Thus, the results of the conducted research show that the change in the shape and dimensions of the weld and the increase in the gap size between the edges can reduce the distribution and values of stresses and deformations under static tension.

5. CONCLUSIONS

- The Simulation calculation module and the SolidWorks software package have helped to define the optimal shape and dimensions of the weld, which may serve the basis for calculating the process parameters for welding the studied structure.
- Having compared the models with different weld cross-sections it has been found out that the weld height and width in the structure under study do not significantly affect the stress concentration.
- The stress concentration and value mainly depend on the shape of the root bead and the gap size between the welded parts.
- The obtained theoretical and practical dependencies allow to make welded joints of consistent quality and reliability and to meet the performance requirements for the weld with minimum material and labor costs.

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