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Technology and equipment for friction stir preweld edge preparation

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Introduction. Friction stir welding is widely used due to certain advantages of this method. Factors that reduce the strength of joints made of high-strength aluminum alloys are considered. When welding flat sheets, an effective way to increase the strength of the weld is edge thickening. The paper proposes a method for such thickening. A device is developed, calculations and experiments are carried out.

Materials and Methods. Laboratory equipment has been developed to provide simultaneous thickening of two edges to be welded. The main component of this equipment is a steel roller, which is rolled along the edges of two blanks and thickens them due to plastic deformation. The same setup can be used for the friction stir welding process. To calculate the geometry of the thickened edges and the parameters of the deforming roller depending on the value of the edge settlement, a mathematical model based on the contact problem for elastic (roller) and elastoplastic (blank) bodies with a bilinear hardening law has been developed. A three-dimensional simplified geometric model of the facility with account of its symmetry has been constructed. On the contact surfaces, special contact finite elements were selected and the finite element mesh was refined. The numerical implementation of the model was carried out in the ANSYS package.

Results. The theoretical model provides assessing the stress-strain state of interacting elements. On the basis of the developed finite element model, the parameters of the thickened edges are calculated, and the geometry of the thickened edges is defined. Using the developed laboratory equipment, full-scale experiments on thickening the edges of the blanks were carried out. The experimental results confirm the adequacy of the developed theoretical model and calculations based on it. The possibility of adjusting the size of the thickened edges is shown.

Discussion and Conclusion. A technology for obtaining thickened edges in places of welds is proposed. It will reduce the metal consumption of structures and ensure the bearing capacity of welded joints not lower than similar characteristics of the base metal. A theoretical model of the process is developed, and a numerical experiment providing the selection of the process parameters is carried out.

Keywords: friction stir welding, thickened edges, computer model, geometry and dimension of edges, bearing capacity of welded joints.

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Introduction. Many researchers[1] [1–5] report on the high level of mechanical properties of joints made by friction stir welding (FSW) and the advantages of this welding method. Issues related to the calculation of temperature fields under FSW are considered in [6]. However, during FSW of aluminum alloys, whose high strength is achieved by

[1] Sergeeva EV. Friction stir welding in the world shipbuilding. Current level of development, prospects, equipment. HSC Consulting. URL: WWW.sergeev-hsc.de (accessed 12.09.2011). (In Russ.)

heat treatment or strengthening deformation, the strength of welded joints is 0.78–0.94 of the strength of the base metal[2] [7, 8]. In these cases, it is possible to compensate for the missing strength through increasing the thickness of the metal in the places of welds or by introducing a safety factor. The latter increases the weight of the structure and, accordingly, makes it uneconomic. A review of recent studies on the dependence of mechanical and microstructural properties of welds under FSW with the use of cooling is presented in [9]. In [10, 11], the optimization of the FSW process in the connection of aluminum alloys is considered. The effect of cryogenic treatment and annealing on the microstructure of the weld during FSW is considered in [12]. Methods for achieving increased joint strength are investigated in [13]. The impact of the axial force under FSW is studied in [14]. Theoretical and experimental studies of FSW joining dissimilar materials and the effect of technological parameters of the process on its strength are considered in papers [15, 16].

There are several ways to thicken the edges at the welding sites. They are obtained through mechanical or chemical milling[3, 4] by artificial thinning of the base metal, with the exception of the zone where the connection is made by welding. However, these operations cause a reduction in the material utilization factor to 0.5–0.7 and an increase in the construction cost. In addition, these processes are very labor-consuming.

Sometimes the thickening of the welded edges is obtained through surfacing, which causes the appearance of high residual stresses, an increase in welding deformations, and a decrease in the efficiency of the use of high-strength alloys[5].

The objective of this study is to develop and test the edge thickening technology under FSW, which will increase the material utilization rate, reduce labor costs, increase the bearing capacity of weld joints to the level of the base metal and increase the fatigue strength of the joints.

Materials and Methods. The following requirements are specified to the geometry of the thickened edges shown in Fig. 1.

First, the height of the edge thickening h should compensate for the missing strength of the weld joint caused by the thinning of the weld by the tool shoulders and the softening of the alloys in the heat-affected zone. Usually, for high-strength aluminum alloys, this value is 10-25% of the strength of the base metal. In this regard, h= (0.1–0.25) S, where S — thickness of the base metal.

Secondly, the width of the edge thickening b should be greater than the diameter of the tool shoulders for the FSW.

Thirdly, the width of the plastic deformation zone B, as shown in Fig. 1, should overlap the heat-affected zone formed under FSW.

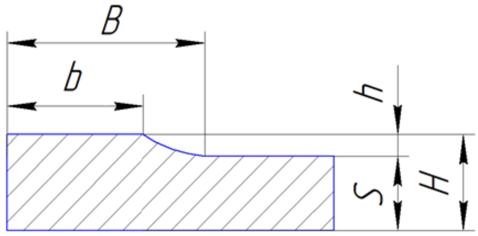

Fig. 1. Thickened edges geometry: S — metal thickness; B — width of plastic deformation zone; b — width of edge thickening; h — height of edge thickening

[2]Technology. Properties of joints obtained by FSW. Available from: http://referatwork.ru/category/tehnologii/view/492395_svoystva_soedineniy_poluchennyh_stp (accessed 20.08.2018). (In Russ.)
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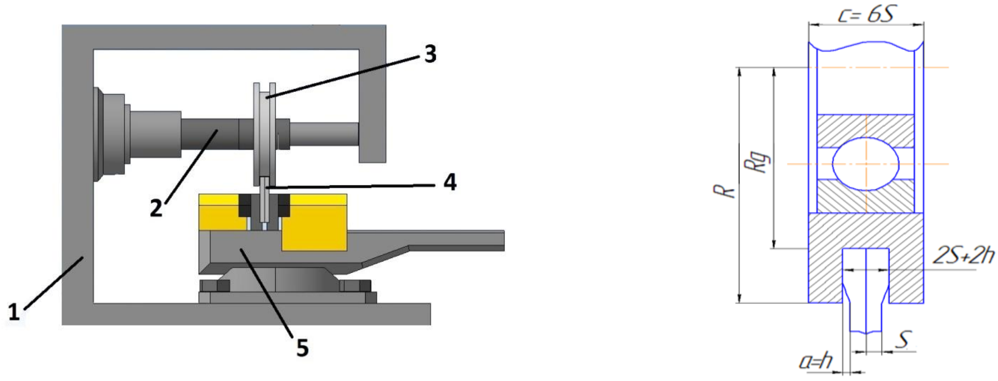
[4] Karachenkov EM. Improving the quality of body parts of rocket and space technology: Cand.Sci. (Eng.) diss., abstract. Khrunichev Space Research Center. Moscow, 2000. (In Russ.)
[5] Kapyrin GI, Grishchenko LV, Kurkin SA, et al. Improving the fatigue strength of welded joints. USSR Patent, 1973. (In Russ.)

The process of thickening the welded edges is proposed to be performed by cold rolling. Figure 2 shows the installation scheme for one-sided thickening of two edges that are to be welded at the same time. Moreover, this operation can be performed on the same equipment on which the welding will be carried out later.

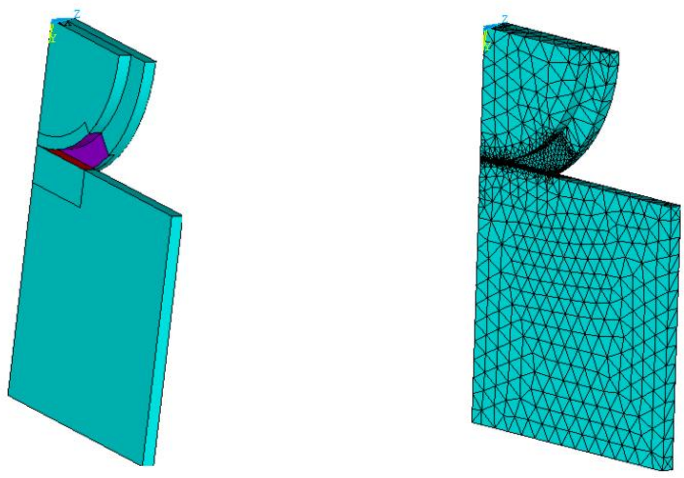


a) *b*)

Fig. 2. Installation for edge thickening under FSW:
a) general view of the installation; *b*) scheme of edge thickening

The installation for edge thickening consists of a universal milling machine 1, on whose rolling pin 2 a deforming roller 3 is installed. Vice 5 is placed on the machine table, in which two blanks 4, whose edges are subjected to thickening, are fixed simultaneously. The installation operates as follows. Thickening blanks are installed along the deforming roller stream. Raising the table creates a predetermined amount of edge settlement. Moving the table along the roller stream is activated. In this case, upsetting of the welded edges occurs by value Δ along the entire length of the blanks.

To calculate the geometry of the thickened edges and the parameters of the deforming roller, depending on the amount of edge upsetting Δ, a computer model has been developed that operates in the finite element package ANSYS. The contact static problem of pressing the roller into the blanks is considered (Fig. 2 b). Due to the symmetry of the problem, a simplified design is considered (Fig. 3 a) It is obtained through dissecting the original with two vertical planes (the plane between the blanks and the plane passing through the roller axis), on which the symmetry conditions are set, and with one horizontal plane (the plane passing through the roller axis), on which a vertical displacement is set (upsetting of the blank edges).



a) *b*)

Fig. 3. Model of the contact interaction of the roller and the blank:
a) geometric model; *b*) finite element model

The developed model uses a linear elastic material for the deforming roller and a bilinear elastic-plastic material without hardening — for an aluminum blank. The surfaces of possible contact are highlighted (Fig. 3 a), contact elements are set on them, and the finite element grid is refined (Fig. 3 b). The model provides evaluating the stress-strain state of interacting structural elements in the elastic and plastic regions, as well as determining the geometry of thickened edges.

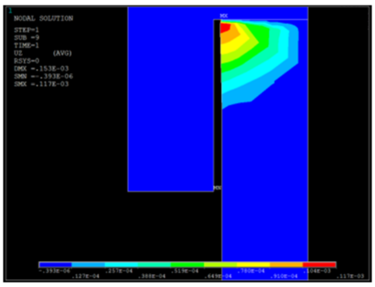
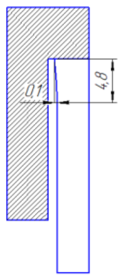
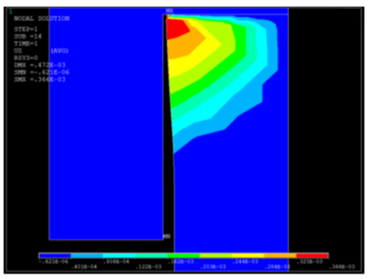
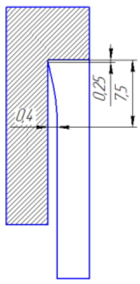
The initial data for the model operation are:

— amount of upsetting of the welded edges Δ, mm;
— thickness of the welded blanks *S, mm*;
— width of the edge thickening $b \geq d/2$, *mm*, where *d* — shoulder diameter;
— plastic deformation zone $B \geq T/2$, where *T* — heat-affected zone under FSW, *mm*;
— edge thickening size $h = (0.1–0.25)\ S$, *mm*;
— thickness of the preweld edges $H=S+h$, *mm*;
— deforming roller radius $R_\partial \geq 70$ *mm*;
— roller outer radius $R_0 = R_\partial + B$, *mm;*
— gap between the side surfaces of the roller and the blanks $\alpha = (0.1…0.25)\ S$, *mm*;
— width of the roller $C = 6S$, *mm;*
— elastic modulus of the aluminum blank E = $0.7 \cdot 10^5$ MPa;
_ elastic modulus of the steel deforming roller E = $2{,}1 \cdot 10^5$ MPa;
— Poisson's ratio $\mu = 0.33$;
— ultimate strength of the base metal σ_b=390 MPa;
— yield strength of the base metal, σ_T=175 MPa.

Research Results. The geometry of the thickened edges as a result of their upsetting by value Δ can be inferred by the pattern of the distribution of axial displacements in the deformable edges. Table 1 shows the distribution of stresses in blanks with a thickness of 4.0 mm, the geometry and dimensions of thickened edges with varying degrees of upsetting.

Table 1

Distribution of transverse displacements on deformed blanks with a thickness of 4.0 mm and the geometry of thickened edges with varying degrees of upsetting

Distribution of transverse displacements in the blanks under edge upsetting	Geometry and dimensions of thickened edges, mm	Amount of edge upsetting Δ, mm
		0.1
		0.3

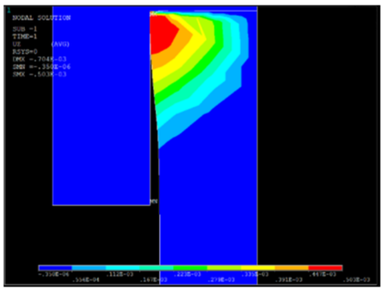
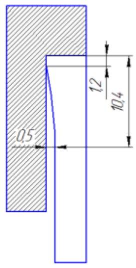
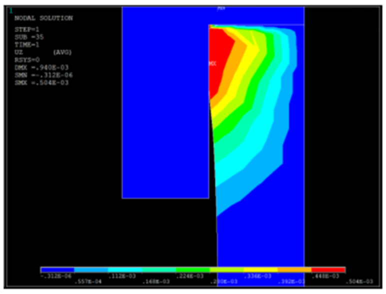
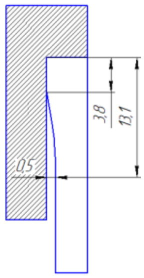
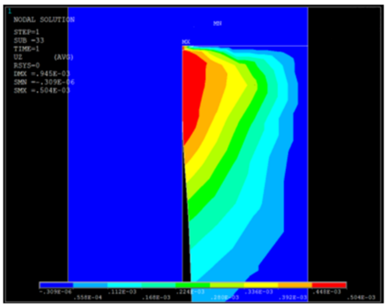
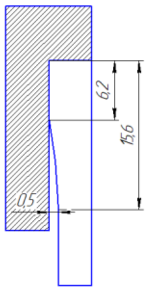
Distribution of transverse displacements in the blanks under edge upsetting	Geometry and dimensions of thickened edges, mm	Amount of edge upsetting Δ, mm
		0.5
		0.8
		1.2

Table 2 shows the parameters that characterize the geometry of thickened edges at varying degrees of upsetting Δ.

Table 2

Dimensions of the thickened edges, depending on the degree of their upsetting

Calculated parameters of thickened edges, mm	Amount of edge upsetting Δ, mm					
	0.1	0.3	0.5	0.8	1.2	1.5
Height of thickened edges *h*	0.1	0.4	0.5	0.5	0.5	0.5
Width of plastic deformation zone *B*	4.8	7.5	10.4	13.1	15.6	17.8
Width of thickened edge *b*	0	0.25	1.2	3.8	6.2	8.65
B-b	4.8	7.25	9.2	9.3	9.4	9.15

Figure 4 shows dependences B and b on Δ constructed according to the data presented in Table 2.

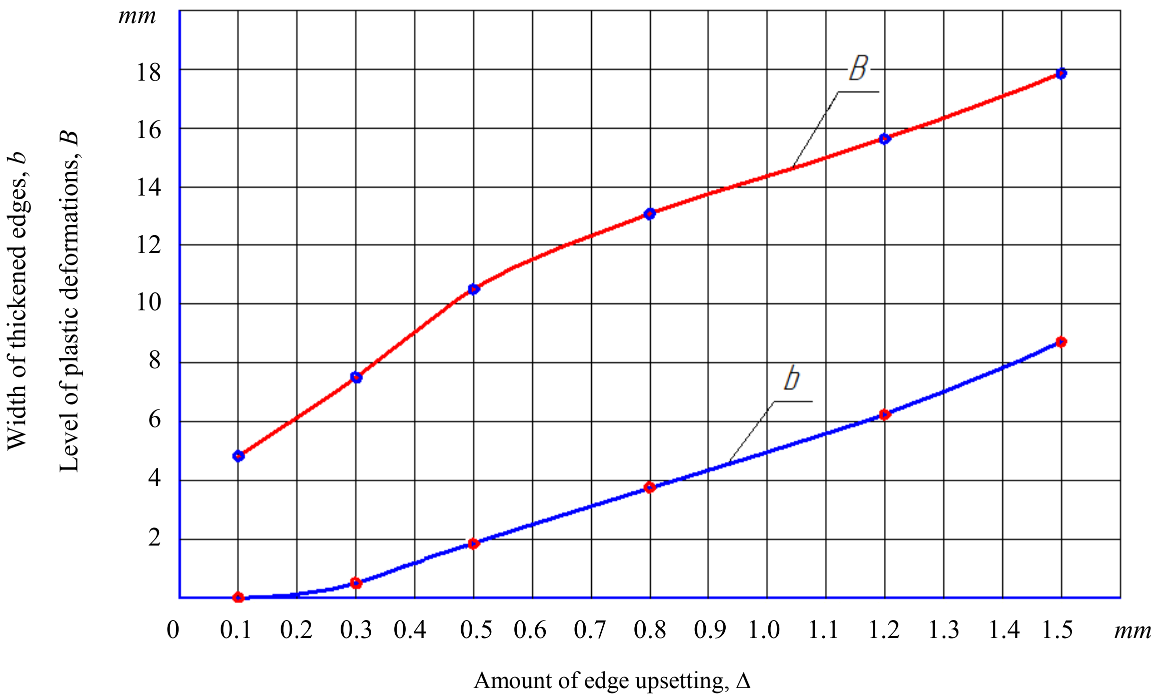


Fig. 4. Width of thickened weld edges *b* and zone of plastic deformations *B,* depending on the amount of edge upsetting Δ

It should be noted that at Δ≥0,5 the value (*B-b)* is almost the same and approximately equal to 9.2 mm. With such dimensions, the angle of approach of the weld joint to the base metal φ is less than 1 degree. In this regard, the stress concentration coefficient tends to unity.

Thus, it can be argued that weld joints made through FSW along thickened edges will have high resistance to the origin and development of destruction.

To check the adequacy of the edge thickening calculation model using FEM, its consistency with practice was determined. For this purpose, thickened edges were obtained on the above equipment with upsetting of 0.5 and 1.2 mm. Profilograms of thickened edges obtained on a two-dimensional measuring instrument DIP-6 are shown in Fig. 5.

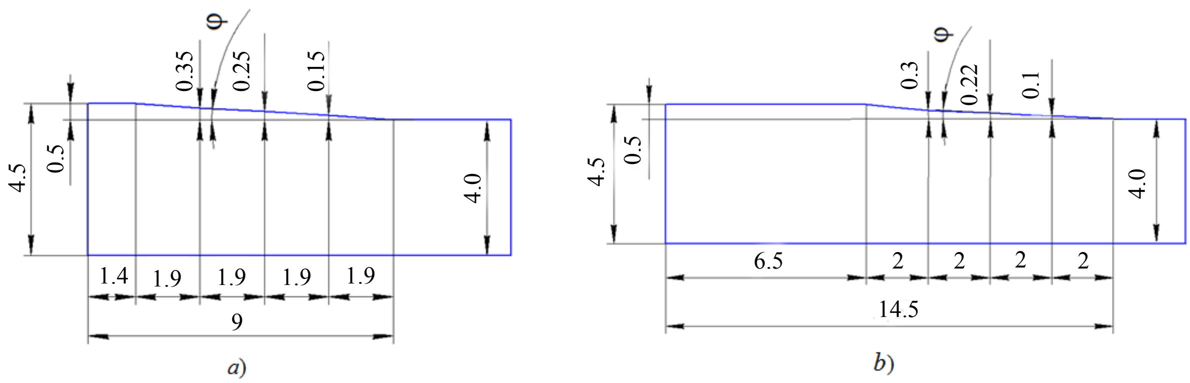


Fig. 5. Geometry of the thickened edges after their upsetting by the value:

a) 0.5 mm; *b*) 1.2 mm

It can be seen that the dimensions of the thickened edges obtained by calculation using FEM are in good agreement with the experimental data. The discrepancy does not exceed 15 %.

Discussion and Conclusions. The paper proposes a new technology for obtaining thickened edges in the places where welded butt joints are made. A laboratory installation to implement the proposed method has been developed. The main element of this installation is an upsetting roller, which acts on the edges of the welded elements and due to plastic deformation causes thickening of these edges. The dependence of the width of the thickened part on the upsetting of the roller is experimentally investigated. A mathematical model of the deformation process has been developed to select this upsetting for a given thickening width for materials that differ in geometry and mechanical properties. This model is implemented in the finite element package ANSYS. A numerical experiment was carried out for the material and geometry considered in this paper. The results agree with the experimental data and confirm the proposed model adequacy. Thus, the proposed technology has been validated, which provides reduction of the metal consumption of structures and the strength of joints not lower than the strength of the base metal. The developed computational model of the edge thickening process allows us to find the amount of upsetting of the deforming roller to create the required width of the thickening.

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Claimed contributorship

Y. G. Lyudmirsky: problem statement; development of a laboratory installation scheme; text preparation. A. N. Soloviev: development of a mathematical and computer model; computational analysis; the text revision; correction of the conclusions. M. V. Soltovets: creating a laboratory installation; conducting the experiment. R. R. Kotlyshev: creating a laboratory installation; analysis of the research results. I. V. Mironov: creating a laboratory installation; discussion of the results. A. V. Kramskoy: creating a laboratory installation; discussion of the results.

All authors have read and approved the final manuscript.