DOI: http://dx.doi.org/10.15407/tpwj2019.04.02

STRESS CONCENTRATION IN BUTT WELDED JOINTS WITH REINFORCEMENT FROM ONE SIDE (Review*)

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The strength of parts and structural elements in the presence of welds largely depends on the design of their joints and assemblies. A sharp change of geometry in their vicinity causes the appearance of additional local stresses or their concentration. The value of these stresses depends on the structural shape of mating of separate elements. That is why they can affect the strength of welded structures in a different way. Stress concentration in the zone of transition from the weld to the base metal has a significant effect on joints fatigue resistance. At the elastic deformation, the theoretical stress concentration factor serves as a quantitative measure of stress concentration. It does not depend on properties of the material, and at a preset type of deformation its value is influenced only by geometry parameters of the stress concentrator, such as its shape and relative dimensions. In practice, the theoretical stress concentration factor is determined by approximate dependencies, as well as by analytical, experimental and numerical methods for investigation of stressed state. The description and analysis of these methods are the aim of the presented review. 37 Ref., 2 Figures.

Keywords: *butt welded joint, reinforcement from one side, axial load, stressed state, tension, bending, stress concentration*

At static loading effect of concentration is insignificant, since failure takes place under effect of stresses that exceed yield point of part material, and it is preceded by considerable plastic deformations, due to which inhomogeneity of stress distribution is reduced on contour as well as part section. However, great number of machine parts and elements of structures of general and special designation take up during operation a lot of changes of temporary loads, for example, moving cargos, transport, waves, wind etc. Changing loads that appear at that can provoke fatigue fracture of these structural elements.

Fatigue fracture differs from static one by the fact that it can be a consequence of application of not high stresses, sometimes significantly smaller than the yield point (multicycle fatigue), therefore, usually it takes place without noticeable preliminary macroplastic deformation. Therefore, effect of stress alignment, after reaching the yield point, is absent, so cyclic loads are sensitive to stress concentration, and various types of grooves, fillets, holes, undercuts, transitions of welds to base metal etc. are the potential places of preliminary nucleation of fatigue cracks.

In butt welded joints formation of a zone of higher loads is caused by weld reinforcement, and technology and mode of welding determine its main parameters. Thus, appearance and size of weld in arc welding depend on a method of welding, welding consumables, type of groove preparation, etc. For example, according to GOST 14771-76 C7, C25, C26 and C27 joints have similar reinforcement size on face and root sides and C2, C4, C9, C17, C18 and C22 joints can be made without reinforcement on the root side, i.e. they can be reinforced from one side.

The main geometry parameters of butt welds are width *g* and height *h* of weld reinforcement, fillet angle θ and radius of transition from weld to base metal *r* (Figure 1). Width and height of the reinforcement determine a general profile of butt weld, whereas fillet angle and radius of transition from weld to base metal characterize sharpness of concentrator in the local zones [1]. Therefore, in the case of ideal butt welded joint without such defects as linear and angular deformations in process of welding, a theoretical stress concentration factor (SCF) is determined by two independent constituents, first of which (structural SCF) $\alpha_{\sigma g}$ is provoked by general geometry of weld-

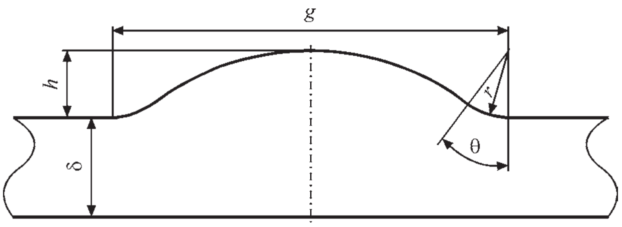

Figure 1. Main geometry parameters of butt welded joint with reinforcement from one side

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[*] The publication contains the results of investigations carried by grant of the President of Ukraine and completive project F75 of the State Fund of Fundamental Investigations.

ed assembly and thickness of joining elements, and second (local SCF) $\alpha_{\sigma w}$ is the geometry of transition zone from weld to base metal [2]. Then, the maximum stresses $\sigma_{\max}$ will be determined by formula

$$\sigma_{\max} = \alpha_{\sigma g}\alpha_{\sigma w}\alpha_{\text{nom}}, \qquad (1)$$

where σ_{nom} is the nominal stresses that act at a distance from concentrator.

In practice such an approach is realized in a hot point stress method, which was developed by the researchers of The Welding Institute, in particular, Maddox S. J and Niemi E. [3, 4], and German researcher A. Hobbacher to solve the problems of fatigue strength of welded assemblies. Effect of general joint geometry and geometry of mating zone of weld to plates being welded on life of structural element for given variable loading in the indicated method are considered separately in calculations.

Since a stress gradient in zone of transition of weld to base metal is very high, the stresses calculated using a finite element method (FEM) in this zone are very sensitive to size of finite element grid [6]. Therefore, the structural constituent of stresses caused by general geometry of the joint is determined applying a computer model of investigated welded assembly, which does not include weld, by means of extrapolation of stresses calculated in the reference points at some distance form the weld. In particular, at linear extrapolation the reference points are located at 0.5δ and 1.5δ distance from the fusion line of weld to base metal on joint surface.

Number of cycles before failure of assembly at preset value of variable load can be obtained by marking a found value of a range of structural stresses, i.e. which were determined by structural SCF $\sigma_{\alpha g}$, on a fatigue curve for butt welded joint in FAT (File Allocation Table) catalogue. Application of these catalogues in calculations allows taking into account effect of weld, since these catalogues contain series of fatigue curves obtained by the results of fatigue tests of real welded elements and expressed in values of the range of nominal stresses independent on a factor of cycle asymmetry at load application [7].

Obviously, that the fatigue curves of the real welded joints take into account effect on fatigue resistance of residual welding stresses and mechanical inhomogeneity of regions on heat-affected zone, but this approach does not provide the possibility to determine local stressed state in some vicinity of the stress concentrator. Therefore, the methods based on determination of effective local SCF $K_{\sigma w}$ are used in the fatigue calculations. It depends not only on geometry shape of transition zone from weld to base metal, but also from some constants of the material, such as factor of sensitivity to stress concentration [1], critical distance [8] or size of structural element [9].

The most widespread is application of a practice for determination of effective local SCF in form of a method of factious rounding of stress concentrator proposed by German researcher D. Radaj [10]. This method is based on the assumption that in calculation of theoretical local SCF $\sigma_{\alpha w}$ the value of actual radius of concentrator curvature is taken, and the value of factious radius, which is determined by minimum dimensions of structural element and rigidity of stressed state [11], are taken for calculation of effective local SCF $K_{\alpha w}$.

Based on the results of fatigue testing of over 1000 samples of welded joints of different shape and size it is determined that a joint radius of the effective concentrator for steel makes 1 mm [12]. Evaluations of effective local SCF, as a rule, are made based on known theoretical local SCF, and its real value is determined experimentally as a relationship of endurance limit of smooth sample to endurance limit of sample with stress concentrator [1]. So, application of a universal factious radius for whole class of materials can provide the results different from the experiment.

It is necessary to remember that the considered method can be used only for determination of fatigue resistance characteristics, however, the experience shows that stress concentration shall be taken into account not only at effect of vibration loading, but at static loading and impact, if brittle fracture of the structure is possible. Thus, at operation of welded joints under low temperature conditions the transition of metal into a brittle state depends on the operating temperature as well as other factors, in particular, on stress concentration. The latter for structures of cryogenic engineering is one of the most important factors that determine their strength and life [13]. Therefore, evaluation of the theoretical local SCF is one of the main measures for preliminary fracture of welded assemblies and structure elements.

Analytical strength calculations of welded joints based on the methods of material resistance do not consider the peculiarities of conditions of stress distribution in the places of change of structure element shape, therefore they can not be used for solution of the problems of stress concentration determination.

The elasticity theory, which is free of many assumptions accepted for simplification in material resistance, allows solving the problems, which are out of limit range applied by these assumptions, and is more general theory, but at the same time is more compound, and its application in many cases is accompanied by complex calculations.

The problem can be significantly simplified in a series of cases using a method of sections. It lies in a division of complex welded joint on a series of simple elements with replacement of weld reinforcement by equivalent work of corresponding forces that allows using known in advance solutions of elasticity theory.

Due to weld reinforcement in the area of increase of transverse sections the projecting parts limit the deformations of main elements of joint. This provokes local distortion of sections and change of the conditions of distribution of power flow. Limiting effect of the projections can be considered equivalent to the effect of some surface horizontal forces, which are tangential stresses applied in the reinforcement place [14].

Using a method of sections it is possible to eliminate the local reinforcement and replace their effect by work of equivalent forces, and then the calculation scheme of welded joint can be presented in form of a main element of constant transverse section without shape change. It in addition to external load is also effected by some more forces applied in the points of imaginary detachment of the projecting parts (Figure 2).

Knowing the law of distribution of equivalent forces it is possible to use already known solutions in the elasticity theory as for band loaded at the edges or ends with distributed normal or tangential forces [15] and determine normal stresses in the places of geometry inhomogeneity of butt welded joint.

Closed-form solution of the problem was obtained in work [14] using the method of sections for simplified model of butt joint with rectangular reinforcement.

Consideration of curvilinear shape of the projections of real butt welds significantly complicates differential equation for determination of equivalent tangential stresses, applied in the place of conventional detachment of projection. Even using simplified model of projection in form of symmetric relatively to weld axis inclined straight lines [14] this equation appears to be a linear inhomogeneous differential equation of second order with variable factors.

Fulfillment of the requirements at the boundary with the projection similar by shape to butt weld reinforcement is possible in curvilinear coordinates, but then the problem appears with meeting the conditions at straight line boundary. Therefore, for the first time German researcher H. Neuber has found an analytical solution of the plane problem of elasticity theory as for tension of semi-infinite plate with the projection [9]. He selected such a system of orthogonal curvilinear coordinates that one of the coordinate lines develops a projection, and stress function, which satisfies problem boundary conditions, was determined. The maximum stresses on the joint contour and geometry of the projection were determined through the contour line parameter, however, it is impossible to set a feedback between this parameter and sizes of the projection. Therefore, dependence of the maximum stress on *g*/*r* relationship is presented in form of diagram. It is necessary to take into account that this diagram can only be used for projections with $g/2r \geq 4\sqrt{3}$ relationship. It is related with the fact that a half-width of the projection is a distance from its symmetry axis to point, in which the contour is parallel to this axis. In the projections, size of which does not meet this requirement, such a point is absent in general, and the contour parameter is a complex number. Thus, it is impossible to determine the maximum stresses in this range [16].

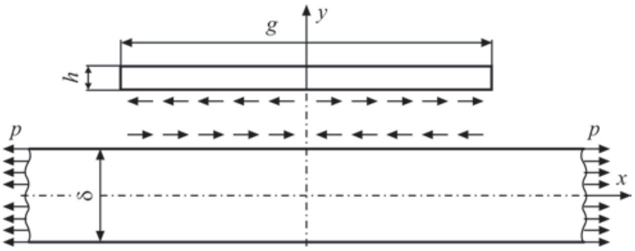

Figure 2. Scheme of loading of separate parts of model of butt welded joint with rectangular projection

Besides, the dependence of the maximum stress on *g*/*r* relationship stipulates increase of the maximum stress not only with decrease of radius of weld to base metal transition, but with increase of width of projection that is not provided by experimental data. In particular, in work [17] for the simplified models of welded joint with $r = 0.5$ and $h = 5$ mm it was determined using a polarization-optical method that a value of local SCF at axial tension with increase of weld width from 5 to 25 mm reduces from 1.60 to 1.59, and its maximum value 1.61 was registered at $g = 8$ mm. Such insignificant deviations of local SCF values to increase as well as decrease side, are more likely related with the measurement error or deviation of other geometry sizes of the models that can make a basis for conclusion that it does not depend on projection width.

A single parameter of the contour line, which in work [9] set the sizes and shape of the projection, does not allow setting main geometry characteristics of weld reinforcement independent one from another. Therefore, in work [18] more general problem of elasticity theory was solved using conformal mapping method. A mapping function was set in form of series, keeping the larger number of terms of which it is possible to reduce the radius of projection mating with the plate, and varying the factors at its terms change the *h*/*g* relationship.

The disadvantage of such approach is the fact that size and shape of the projection, as in [9], are determined by the parameters of contour line that are set by mapping function. Therefore, an approximation formula for determination of local SCF in the butt welded joint of sufficiently large thickness can be determined only by means of statistical processing.

Since in conformal mapping of a region defined by unit circle or region that lies out of this circle on closed polygonal obtaining the region with set relative size is sufficiently difficult problem, therefore, in order to take into account effect of all parameters that determine shape of real welded joints, on stressed state, it is necessary to analyze the functions with considerably large number of series terms.

A formula for determination of theoretical local SCF was obtained thanks to application of a numerical algorithm of conformal mapping of set singly-connected regions by a method of joint interpolation of coordinates of node points and plotting the mapping functions on large number of these points in work [19] by means of approximation of analytical solutions. However, according to this formula given SCF reduces with rise of thickness of plates being joined, that is not proved by the results of calculations using FEM [20], which showed that the local stresses rise with increase of thickness.

Uncertainty of the results obtained using such an approach as for final regions of types of plates of variable thickness is explained by the fact that presenting the mapping functions in form of a series can provoke appearance of variations of contour stresses due to insufficient smoothness of the obtained contour. Therefore, consideration of effect of the plate thickness was achieved by means of processing of additional experimental data that allowed obtaining the formula [21]

$$\alpha_{\sigma w} = 1 + \frac{1}{\sqrt{r\left(\frac{14}{g} + \frac{1.7}{h} + \frac{5}{\delta}\right)}}. \qquad (2)$$

Development of computer engineering and numerical methods for solution of elasticity theory problems, in particular, FEM resulted in the fact that traditional experiments on determination of stressed state in the zones of concentration on full-scale samples were replaced by numerical experiments based on finite element models. Statistical processing of the results of analytical or numerical solutions of elasticity theory problems or experimental data provides the possibility to get empirical dependences for determination of local SCF, which have general view

$$\alpha_{\sigma w} = 1 + \mathrm{Ar}^{-n}, \qquad (3)$$

where A is the parameter that takes into account macrogeometry of the joint and conditions of its loading.

Large amount of proposed dependencies of type (3) provokes some difficulties in solution of the issue, which of them should be used in each specific case. Thus, following data of review [22] the index of level n in these dependencies is changed in 0.3–0.67 range.

Authors of work [23] by means of corresponding statistical processing of the calculation results using the most widely used formulas of theoretical local SCF at set values of numerical parameters, which characterize shape of weld, determined that Berezovskii–Bakshi formula is the most versatile at variation in wide range of geometry parameters and recommended for practical application

$$\alpha_{\sigma w} = 1 + \left(\frac{r}{h\tan(\theta/2)} + 4\frac{r}{\delta} + 5\frac{r}{r+g}\right)^{-\frac{2}{3}}, \qquad (4)$$

which for butt welded joints with reinforcement from one side provides the reliable result at relationships $r/\delta = 0.01$–0.1 and $h/\delta = 0.1$–0.2.

The problem is in the fact that thin-sheet joints do not correspond to reliability fields for this and other formulas analyzed in work [23]. Thus, for butt welded joints of type C7 according to GOST 8713–79 at thickness of welded plates δ = 2–3 mm the reinforcement height h can vary in 0.5–2.5 mm range, respectively h/δ relationship lies in 0.17–1.25 range.

Irrelevance of calculation data, obtained at empirical formulas from work [23], to a zone of «reliable recommendations» at tension of small thickness welded joints, asymmetric relatively to axis of application of external loading, can be explained by additional bending, promoted by this asymmetry.

These circumstances were outlined by Belarusian researcher Yu.O. Tsumarev in work [24], where he indicated that presence of bending stresses in thin-sheet welded joints with reinforcement from one side results in significant rise of sum stresses in the root part and its decrease in the face part of weld. Based on data of this work axial tension of 200 MPa loading of butt welded joint with h/δ – 0.5 relationship provokes the maximum stresses of 240 MPa in a zone of weld to base metal transition and in the root part in a region with reinforcement it is 260 MPa. Obviously, that the maximum stresses in a weld to base metal transition zone can be determined using local SCF $\alpha_{\sigma w}$, calculated by any of the formulas given in [23]. However, the maximum stresses act on the root side, where local stress concentrator is absent ($\alpha_{\sigma w} = 1$), and additional bending stresses are taken into account with the help of structural SCF $\alpha_{\sigma g}$, which according to [25] is determined by formula

$$\alpha_{\sigma g} = \frac{\delta(\delta + 4h)}{(\delta + h)^2}. \qquad (5)$$

The results of calculation of Yu.O. Tsumarev are proved by the experimental data accumulated during many years in a department of strength of welded joints at the E.O. Paton Electric Welding Institute of the NAS of Ukraine as a result of multicycle fatigue testing of butt welded joints of aluminum alloys. They showed that initiation of fatigue fracture is sometimes started from the root side of weld in thin-sheet butt joints with reinforcement from one side.

Work [25] for determination of stresses on the root side of the weld σ_r proposed a formula

$$\sigma_r = P\frac{\delta + 8e}{(\delta + 2e)^2}, \qquad (6)$$

where P is the axial load that acts on unit of width of welded joint; e is the eccentricity of applied axial loading.

Following the manipulations of work [25] the stresses on the face side of weld (α_f) can be determined by formula

$$\sigma_f = P\frac{\delta - 4e}{(\delta + 2e)^2}. \tag{7}$$

Analysis of this formula shows that it really does not take into account geometry parameters of the zone of weld to base metal transition and increase of stresses on face side of the joint, which, as it is known, for fulfillment of equilibrium conditions in the corresponding sections have to be compensated by some decrease of stresses on the root side. Therefore, the real pattern of stress fields is often determined using FEM computer modelling. However, the significant disadvantage of such approach is the fact that modelling varies height and width of reinforcement [26] and smooth transition on radius from weld metal to base metal is not modeled, regardless the known fact that this radius has a dominant effect on value of the maximum stress [27, 28].

If local SCF is calculated without consideration of fillet radius then it most likely will characterize not a stressed state of welded joint, but finite element grid [29]. Besides, at presence of sharp concentrators, application of local SCF does not seem to be perspective due to singularity of stresses in their vicinity [30]. In such a case, weld to base metal transition zone can be presented from point of view of fracture mechanics as angular cutoff with known distribution of stresses close to its tip [31].

Amount of finite elements necessary to get reliable results is very large at small relative radiuses of transition from weld to base metal (side of element not more than 10 % of radius). Performing the calculations with such detailed approximation of elements is sufficiently difficult. Such calculations require application of high efficiency computation equipment and are carried out only in the exceptional cases [33]. Therefore, to reduce the calculation volume for welded joint it is reasonable to use mathematical formulas for determination of $\alpha_{\sigma w}$ factor, and $\alpha_{\sigma g}$ factor was calculated using FEM and available system of engineering analysis [34].

In the case of action of tensile stresses as well as bending stresses it is impossible to use formula (1), since current procedures [35, 36] lie in determination of structural tensile and bending stresses with further multiplication of each of them on corresponding SCF. Thus, in work [36] it was proposed to decompose the stresses, distributed on the thickness, on tensile-compression stresses (membrane stress) α_m and bending stresses α_b and determine the maximum stresses on formula

$$\sigma_{\max} = \alpha^m_{\sigma w}\sigma_m + \alpha^b_{\sigma w}\sigma_b, \tag{8}$$

where $\alpha^m_{\sigma w}$, $\alpha^b_{\sigma w}$ are the SCF at tension and bending, respectively.

Obviously that in this case it is no need to use structural SCF $\alpha_{\sigma g,}$ since bending stresses are taken into account separately.

Based on hypothesis of broken sections in work [37] there were developed an analytical method for investigation of local stressed state in the zones of stress concentration of butt welded joints with reinforcement from one side. It takes into account eccentricity of application of axial load and local geometry of weld to base metal transition zone. Applying this method the mathematical expressions for determination of stresses on a surface of transition zone of weld to base metal and on weld root side were obtained.

Conclusions

1. Theoretical SCF in butt welded joints is determined by two independent constituents, first of which (structural SCF) caused by general contours of welded assembly and thickness of elements being joined, and second (local SCF) is the geometry of weld to base metal transition zone.

2. Bending stresses, which are taken into account by structural SCF, act as structural constituent of stresses at tension of butt welded joints with reinforcement from one side. If height of reinforcement is comparable with thickness the plates being joined, that is typical for thin-sheet joints, the sum stresses due to tension and bending at weld root side, regardless the absence of local concentrator, can be higher than in the weld to base metal transition zone.

3. Structural SCF for conventional shape of reinforcement can be determined analytically using the materials resistance method or FEM. Limitation of field of application of FEM is related with high labor intensity in designing the accurate, even 2D model with dense local grid. Therefore, for calculation of local SCF the empirical dependencies are used. They were obtained by means of statistical processing of the results of analytical and numerical solutions of problems of elasticity theory or experimental data.

4. Area of reliable and available for today calculation dependencies for determination of local SCF includes the possibility of their application for thin-sheet butt welded joints. Besides, numerical value of local SCF does not provide the information on redistribution of stresses on thickness of joint, in particular, on the weld root side due to their concentration in the weld to base metal transition zone. Therefore, the calculations of joints with reinforcement from one

side can not be limited only by SCF evaluation, and it is necessary to determine the stresses on the face and root sides of weld.

5. The combination procedures are the most effective for determination of stressed state in the vicinity of weld reinforcement. Following to them the stresses in the local zones of weld to base metal transition are determined by mathematical formulas obtained in analytical way and stresses at sufficient distance from the sharp concentrators applying FEM computer modelling.

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Received 22. 01.2019