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PECULIARITIES OF CALCULATION OF STRESS CONCENTRATION FACTORS IN THIN-SHEET BUTT WELDED JOINTS WITH THE CONSIDERATION OF INITIAL ANGULAR DEFORMATION

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ABSTRACT

The paper is devoted to studying the influence of initial angular deformation caused by uneven transverse sagging of the butt weld during cooling on the stress concentration factors (SCF) in the transition zones from the face reinforcement and the weld root to the base metal (BM). An analysis of the existing formulas was carried out to determine the factor that considers the influence of initial angular deformation on the SCF on the fusion line of the weld with the BM. An analysis of the available formulas was carried out to determine the factor that takes into account the effect of initial angular deformation on the SCF on the fusion line of the weld with the BM. As a result, it was found that these formulas were developed for joints with a butt weld symmetrical relative to the median plane of the plates being welded and cannot be used for calculations near the weld root. A theoretical justification is given that initial angular deformation should lead to a decrease in stresses on the root side of the joint. New analytical formulas for the determination of the SCF on the fusion line of the weld root with the BM are proposed, considering initial angular deformation. A specific example was used to show that the presence of initial angular deformation really results in a decrease in stresses on the root side of the joint. The results of analytical calculations were confirmed by numerical calculations using the finite element method.

KEYWORDS: butt welded joint, angular deformation, stress concentration, tension, bending, weld root

INTRODUCTION

During fusion welding of butt welds without edge preparation or with V-shaped edge preparation, the amount of molten metal grows from the back to the facial side of the joint, which causes uneven transverse sagging across the thickness of the joined plates during cooling [1]. As a result, the parts of the joint parallel to the welding are rotated relative to each other by an angle γ, forming an angle between the facial surfaces of < 180° (Figure 1).

Such deviations in geometric shape lead to an increase in stresses in welded joints under their axial loading due to the occurrence of additional bending stresses [2]. It is shown [3], that deviations in the geometric shape occurring during welding have a significant negative impact on fatigue life, especially for thin-sheet structures with low bending stiffness.

Since stress concentration is one of the basic factors that determine the fatigue resistance of welded joints [4], the justification of a procedure for correct assessing the effect of initial angular deformation on the stress concentration factors (SCF) in the transition zones from structural elements of a butt weld to the base metal (BM) is a relevant scientific and technical task in the field of strength, reliability and durability of welded structures.

ANALYSIS OF EXISTING APPROACHES AND MODERN CALCULATIONS

Taking into account the translational and angular mutual displacements of welded plates during the formation of a butt joint, the generalised formula for determination of the theoretical SCF is as follows [5]:

$$\alpha_\sigma = \alpha_{\sigma w}\alpha_m\alpha_\gamma, \quad (1)$$

where $\alpha_{\sigma w}$, α_m and α_γ are the SCF from the weld shape, transverse displacement of welded edges and angular deformation, respectively.

To determine the factor α_γ in joints with a weld symmetrical relative to the median surface of the joined plates, the following formula was proposed in [6]:

$$\alpha_\gamma = 1 + \frac{3l}{\delta}\sin\gamma, \quad (2)$$

where $l/2$ is the distance from the weld edge to the point of application of the axial load P; δ is the thickness of the joined plates (Figure 2).

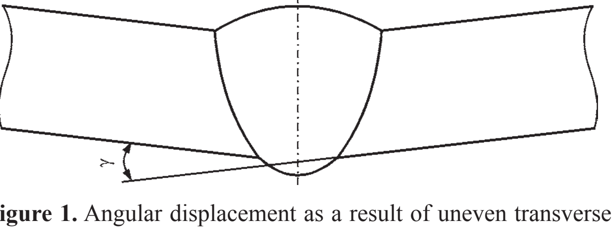

Figure 1. Angular displacement as a result of uneven transverse sagging of the metal during the formation of a butt weld

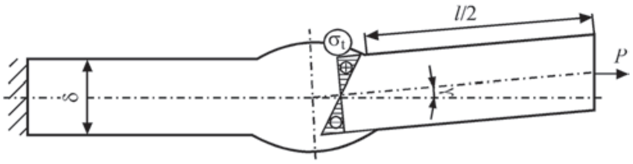

Figure 2. Calculation scheme of a butt welded joint with symmetrical reinforcement and initial angular deformation

According to the recommendations of the International Institute of Welding (IIW) [7], to determine α_γ, the following formula is used:

$$\alpha_\gamma = 1 + \frac{3l\gamma}{\delta}\frac{\tanh(\beta)}{\beta}, \tag{3}$$

where the non-linear factor depending on β takes into account the effect of reducing the initial angle γ as a result of the vertical displacement of the section, to which the axial force is applied [8].

Given that the angle usually does not exceed 5° [9], we can take $\sin\gamma \approx \gamma$ up to the fourth decimal place. Thus, without taking into account the effect of rectification, formulas (2) and (3) can be considered identical.

Considering Figure 2, it can be clearly seen that due to the angular deformation under the action of the axial force *P*, a bending moment M_γ also occurs, which on the fusion line of weld metal (WM) with the BM will be determined by the formula:

$$M_\gamma^f = \frac{Pl}{2}\sin\gamma. \tag{4}$$

Then, tensile stresses from the axial force in the section corresponding to the fusion line are:

$$\sigma^T = \frac{P}{b\delta},$$

and the bending stress in this section from the action of the bending moment is:

$$\sigma^B = \frac{3Pl}{b\delta^2}\sin\gamma,$$

where *T* is the tensile; *B* is bending; *b* is the width of the joined plates.

Therefore, the total stress on the upper side of the joint will be determined as the sum of tensile and bending stresses:

$$\sigma^\Sigma = \frac{P}{b\delta}\left(1 + \frac{3l}{\delta}\sin\gamma\right). \tag{5}$$

As we can see, in the brackets of formula (5), we have the factor α_γ from the formula (2).

Since [6] considered a symmetrical weld, the stresses on the lower side of the joint left ignored, because it is obvious that they will show the difference in tensile and bending stresses (see the diagram in Figure 2) and will be less than stresses on the upper side. At the same time, in [10, 11], when calculating the SCF on the root side of the joints made by one-sided welding, the SCF from the weld shape was also multiplied by the SCF from the angular deformation, as a result of which the total SCF increased, although in fact the initial angular deformation should lead to its reduction near the weld root.

It is known [12, 13] that under both static and cyclic loads, the fracture of thin-sheet welded joints begins namely in the transition zones from the weld root to the BM, so it is necessary to quantitatively consider the effect of initial angular deformation on the value of stresses in these zones.

THEORETICAL FUNDAMENTALS FOR DETERMINATION OF SCF NEAR THE WELD ROOT

According to [14], the bending moment caused by the eccentricity of the axial load applied in the area with the weld on the fusion line of the weld root with the BM in a butt joint without initial angular deformation (Figure 3) will be determined by the formula:

$$M_e = \frac{P}{2}\left(h_f - R_f + \sqrt{R_f^2 - \frac{g_r^2}{4}}\right), \tag{6}$$

where h_f is the height of the facial reinforcement; R_f is the radius of the convex part of the facial reinforcement; g_r is the width of the weld root.

Taking into account the distance between the fusion lines of the facial reinforcement and the weld root with the BM, which is $(g_f - g_r)/2$ (see Figure 3), the bending moment from the initial angular deformation on the fusion line of the weld root with the BM will be determined by the formula:

$$M_\gamma^r = \frac{P\left(l + g_f - g_r\right)}{2}\sin\gamma, \tag{7}$$

where g_f is the width of the facial reinforcement.

Since the direction of the bending moment associated with the initial angular deformation is opposite to the direction of the moment caused by the eccentricity, the final moment on the fusion line of the weld root with the BM is determined as the difference of moments (6) and (7):

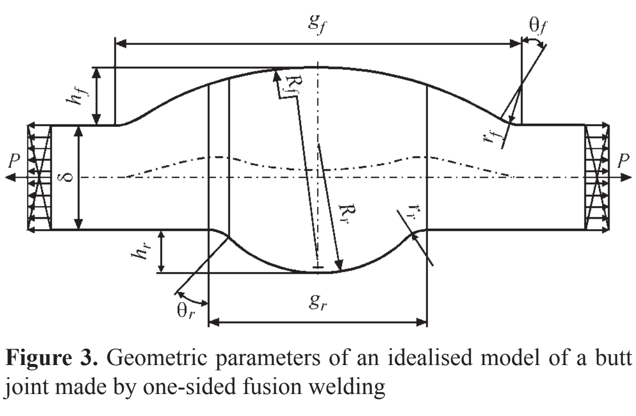

Figure 3. Geometric parameters of an idealised model of a butt joint made by one-sided fusion welding

$$M = M_e - M_\gamma^r =$$
$$= \frac{P}{2}\left[h_f - R_f + \sqrt{R_f^2 - \frac{g_r^2}{4}} - \left(l + g_f - g_r\right)\sin\gamma\right]. \quad (8)$$

If we introduce:

$$m = \delta + h_f - R_f + \sqrt{R_f^2 - \frac{g_r^2}{4}},$$

then, the bending stress on the fusion line of the weld root with the BM for joining a unit width according to [14] at $b_0 \leq \delta/2$ is determined by the formula:

$$\sigma_r^B =$$
$$= \frac{Mm}{2r_r\left[\left(r_r + \frac{m}{2}\right)^2 \ln\frac{r_r + b_0}{r_r} - b_0\left(r_r + m\right) + \frac{b_0^2}{2} + \frac{m^3 + \left(m - 2b_0\right)^3}{24\left(r_r + b_0\right)}\right]}, \quad (9)$$

and at $b_0 > \delta/2$ — by the formula:

$$\sigma_r^B =$$
$$= \frac{Mm}{2r_r\left[\left(r_r + \frac{m}{2}\right)^2 \ln\frac{2r_r + m}{2r_r} - \frac{m}{2}\left(r_r + m\right) + \frac{m^2}{8} + \frac{m^3}{12\left(2r_r + m\right)}\right]}, \quad (10)$$

where r_r is the radius of the transition arc from the weld root to the BM; b_0 is a parameter that characterizes the concentrator sharpness near the weld root and is determined by the formula:

$$b_0 = 4\sqrt{2}\,\frac{r_r h_r}{\sqrt{g_r^2 + 4h_r^2}},$$

where h_r is the height of the weld root.

Substituting the expression for bending moment (8) into (9) and (10), we obtain formulas for the determination of bending stresses on the fusion line of the weld root with the BM in the joint with initial angular deformation, respectively, at $b_0 \leq \delta/2$:

$$\sigma_r^B =$$
$$= \frac{P\left[m - \delta - \left(l + g_f - g_r\right)\sin\gamma\right]m}{4r_r\left[\left(r_r + \frac{m}{2}\right)^2 \ln\frac{r_r + b_0}{r_r} - b_0\left(r_r + m\right) + \frac{b_0^2}{2} + \frac{m^3 + \left(m - 2b_0\right)^3}{24\left(r_r + b_0\right)}\right]} \quad (11)$$

and at $b_0 > \delta/2$

$$\sigma_r^B =$$
$$= \frac{P\left[m - \delta - \left(l + g_f - g_r\right)\sin\gamma\right]m}{4r_r\left[\left(r_r + \frac{m}{2}\right)^2 \ln\frac{2r_r + m}{2r_r} - \frac{m}{2}\left(r_r + m\right) + \frac{m^2}{8} + \frac{m^3}{12\left(2r_r + m\right)}\right]}. \quad (12)$$

The tensile stresses on the fusion line of the weld root with the BM at $b_0 \leq \delta/2$ and at $b_0 > \delta/2$ are determined, respectively, by the following formulas [14]:

$$\sigma_r^T = \frac{P}{r_r\left(\ln\frac{r_r + b_0}{r_r} + \frac{m - b_0}{r_r + b_0}\right)} \quad (13)$$

and

$$\sigma_r^T = \frac{P}{r_r\left(\ln\frac{2r_r + m}{2r_r} + \frac{m}{2r_r + m}\right)}. \quad (14)$$

Therefore, the theoretical SCF on the fusion line of the weld root with the BM at $b_0 \leq \delta/2$ will be determined as the ratio of the sum of bending (11) and tensile stresses to the nominal stress $\sigma_{nom} = P/\delta$ (13):

$$\alpha_\sigma^r = \frac{\delta}{r_r}\left(\frac{1}{\ln\frac{r_r + b_0}{r_r} + \frac{m - b_0}{r_r + b_0}} + \frac{m\left[m - \delta - \left(l + g_f - g_r\right)\sin\gamma\right]}{4\left[\left(r_r + \frac{m}{2}\right)^2 \ln\frac{r_r + b_0}{r_r} - b_0\left(r_r + m\right) + \frac{b_0^2}{2} + \frac{m^3 + \left(m - 2b_0\right)^3}{24\left(r_r + b_0\right)}\right]}\right), \quad (15)$$

and at $b_0 > \delta/2$ — of the sum of stresses (12) and (14):

$$\alpha_\sigma^r = \frac{\delta}{r_r}\left(\frac{1}{\ln\frac{2r_r + m}{2r_r} + \frac{m}{2r_r + m}} + \frac{m\left[m - \delta - \left(l + g_f - g_r\right)\sin\gamma\right]}{4\left[\left(r_r + \frac{m}{2}\right)^2 \ln\frac{2r_r + m}{2r_r} - \frac{m}{2}\left(r_r + m\right) + \frac{m^2}{8} + \frac{m^3}{12\left(2r_r + m\right)}\right]}\right). \quad (16)$$

REFINED APPROACH TO DETERMINATION OF SCF ON THE FACIAL SIDE OF A JOINT

The use of formulas such as (1), which involve multiplying the theoretical SCF at tension by other factors considering additional bending stresses, is not fully correct, since it is known [15] that the theoretical SCFs for tensile and bending stresses in the same concentrator are different.

According to [16], the bending stress on the fusion line of the facial reinforcement with the BM for joining a unit width at $a_0 \leq \delta/2$ is determined by the formula:

$$\sigma_f^B =$$
$$= \frac{M\delta}{2r_f\left[\left(r_f + \frac{\delta}{2}\right)^2 \ln\frac{r_f + a_0}{r_f} - a_0\left(r_f + \delta\right) + \frac{a_0^2}{2} + \frac{\delta^3 + \left(\delta - 2a_0\right)^3}{24\left(r_f + a_0\right)}\right]}, \quad (17)$$

and at $a_0 > \delta/2$ — by the formula:

$$\sigma_f^B =$$
$$= \frac{M\delta}{2r_f\left[\left(r_f + \frac{\delta}{2}\right)^2 \ln\frac{2r_f + \delta}{2r_f} - \frac{\delta}{2}\left(r_f + \delta\right) + \frac{\delta^2}{8} + \frac{\delta^3}{12\left(2r_f + \delta\right)}\right]}, \quad (18)$$

where r_f is the radius of the transition arc from the facial reinforcement to the BM; a_0 is a parameter that characterises the concentrator sharpness near the facial reinforcement and is determined by the formula:

$$a_0 = 4\sqrt{2}\frac{r_f h_f}{\sqrt{g_f^2 + 4h_f^2}}.$$

The tensile stresses on the fusion line of the facial reinforcement with the BM at $a_0 \le \delta/2$ and at $a_0 > \delta/2$ are determined, respectively, by the following formulas [16]:

$$\sigma_f^T = \frac{P}{r_f\left(\ln\frac{r_f + a_0}{r_f} + \frac{\delta - a_0}{r_f + a_0}\right)} \quad (19)$$

and

$$\sigma_f^T = \frac{P}{r_f\left(\ln\frac{2r_f + \delta}{2r_f} + \frac{\delta}{2r_f + \delta}\right)}. \quad (20)$$

It is obvious that the eccentricity on the fusion line is equal to zero, so the bending moment at this point is caused only by the initial angular deformation and is determined by the formula (4).

Since the direction of stresses from the bending moment caused by the initial angular deformation on the facial side of the joint coincides with the direction of stresses from the axial force, the theoretical SCF on the fusion line of the facial reinforcement with the BM at $a_0 \le \delta/2$ will be determined as the ratio of the sum of bending stresses (17), taking into account (4) and tensile stresses (19), to the nominal stresses:

$$\alpha_\sigma^f = \frac{\delta}{r_f}\left(\frac{1}{\ln\frac{r_f + a_0}{r_f} + \frac{\delta - a_0}{r_f + a_0}} + \frac{\delta l \sin\gamma}{4\left[\left(r_f + \frac{\delta}{2}\right)^2 \ln\frac{r_f + a_0}{r_f} - a_0\left(r_f + \delta\right) + \frac{a_0^2}{2} + \frac{\delta^3 + \left(\delta - 2a_0\right)^3}{24\left(r_f + a_0\right)}\right]}\right), \quad (21)$$

and at $a_0 > \delta/2$ — of the sum of stresses (18), taking into account (4) and (20):

$$\alpha_\sigma^f = \frac{\delta}{r_f}\left(\frac{1}{\ln\frac{2r_f + \delta}{2r_f} + \frac{\delta}{2r_f + \delta}} + \frac{\delta l \sin\gamma}{4\left[\left(r_f + \frac{\delta}{2}\right)^2 \ln\frac{2r_f + \delta}{2r_f} - \frac{\delta}{2}\left(r_f + \delta\right) + \frac{\delta^2}{8} + \frac{\delta^3}{12\left(2r_f + \delta\right)}\right]}\right). \quad (22)$$

CALCULATION RESULTS AND THEIR DISCUSSION

Let us consider a butt welded joint of aluminium AMg6M alloy with a thickness of 1.8 mm, for which theoretical SCFs were calculated in [14] on the fusion lines of the facial reinforcement and the weld root with the BM without considering the initial angular deformation (Table 1), and postulate the initial angular deformation $\gamma = 2°$ and the distance from the fusion line of the facial reinforcement with the BM to the point of applying the axial load $l/2 = 3$ mm.

Since $b_0 \le \delta/2$ (see Table 1), the SCF on the fusion line of the weld root with the BM in the studied joint will be determined by formula (15), and as a result, it will be found to be 1.92. If we introduce $\gamma = 0$ in formula (15), we find that in a similar joint without initial angular deformation, the SCF on the fusion line of the weld root is 2.4, which is confirmed by the results of the finite element method (FEM) calculations conducted in [14]. Thus, the presence of initial angular deformation leads to a 20 % reduction in stresses near the weld root.

Also, for this joint $a_0 \le \delta/2$ (see Table 1), so the SCF on the fusion line of the facial reinforcement with the BM will be determined by formula (21), and as a result, it will be found to be 2.14. Introducing $\gamma = 0$ in formula (21), we find that in a similar joint without initial angular deformation, the SCF on the fusion line of the facial reinforcement with the BM is 1.62, which is also confirmed by the results of the FEM calculations carried out in [14]. Thus, the initial angular deformation leads to a 32 % increase in stresses on the facial side of the joint.

The obtained analytical results are in good agreement with the results of numerical calculations by the finite element method (FEM), according to which the maximum stress near the weld root was 2.01 MPa, and near the reinforcement — 2.22 MPa (Figure 4).

Table 1. Geometric dimensions of structural elements of butt joint weld of aluminium AMg6M alloy made by TIG welding

Joint side	Projection width *g*, mm	Projection height *h*, mm	Radius of transition from WM to BM *r*, mm	Radius of the convex part *R*, mm	Concentrator sharpness parameter a_0 (b_0), mm
Facial (*f*)	7.000	1.000	0.690	5.935	0.536
Root (*r*)	3.750	0.750	0.490	2.229	0.515

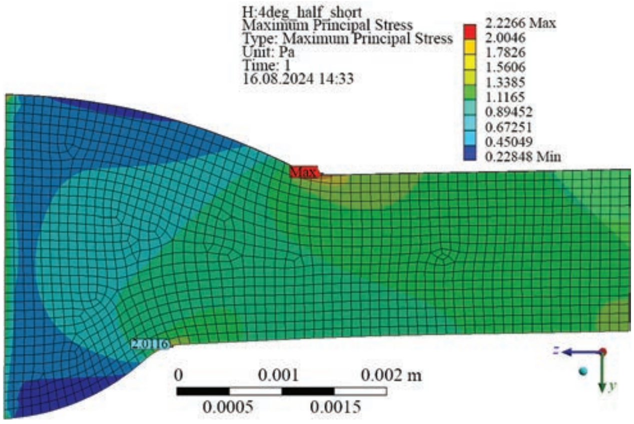

Figure 4. Calculated stress fields in the studied joint with initial angular deformation obtained by FEM

Thus, the stress on the facial side of the joint differ by 3.8 %, and on its root side — by 4.7 %.

The applied axial load was 1.8 N in order that the rated stress in a 1.8 mm thick joint of a unit width was 1 MPa. Thus, the obtained stress values in the concentrator zones were equal to the values of the corresponding SCF, which helped to simplify the comparison of analytical and numerical results.

To prevent the influence of the finite element mesh sizes on the values of maximum local stresses, it was refined during the analysis until the difference between the stress values in the final and previous models was less than 5 % [17]. As a result, the linear size of the final model element was 0.1 mm, and the model itself had 16848 elements with 70308 nodes.

Since $\alpha_m = 1$, the total SCF $\alpha_\sigma = 2.14$, and the theoretical SCF of the weld shape $\alpha_{\sigma w} = 1.62$, according to formula (1), the SCF of angular deformation α_γ according to the refined theory is 1.32, and according to formula (2), which does not take into account the difference between the SCF at tension and bending, this value is almost 1.35. It is expected that the refined calculations are less conservative, as far as for butt welded joints, the SCF at bending is slightly lower than the SCF at tension [18].

CONCLUSIONS

1. An analysis of existing formulas was carried out to determine the factors that take into account the influence of initial angular deformation caused by uneven thermal sagging of butt welds across the joint thickness on the total stress concentration. Taking into account the nature of the analysed formulas, it was theoretically justified that initial angular deformation should lead not only to an increase in stresses on the facial side of the joints, but also to their decrease on the root side.

2. For the first time, analytical formulas for determination of the theoretical stress concentration factor on the fusion line of the weld root with the base metal, which take into account the initial angular deformation, were obtained.

3. The analytical formulas for evaluating the effect of initial angular deformation on the theoretical stress concentration factor on the fusion line of the facial weld reinforcement with the base metal were improved in terms of considering the difference between the stress concentration factors of tensile and bending stresses.

4. On the example of a thin-sheet butt welded joint of aluminium AMg6M alloy, made by TIG welding, it is shown that the presence of initial angular deformation with a value of 2° leads to an increase in stresses on the facial side of the joint by 32 % and to their decrease by 20 % near the weld root compared to the joint without initial angular deformation. The obtained results are confirmed by numerical calculations using the finite element method with a discrepancy of not more than 5 %.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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