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THE INFLUENCE OF A CIRCUAL HOLE ON RESIDUAL STRESS AFTER WELDING OF ALUMINUM

Key words: welding, stress, FEM, aluminium, hole.

Abstract: The location of a hole during the welding of aluminium has an influence on the residual stresses. 2D FEM model of the welded plate, lying on the surface of welded sheets, was used. The calculations were done with ANSYS in two phases, thermal and mechanical calculations of deformations and stresses, with non-linear, temperature dependent material properties. Different locations of the hole were used. Residual stresses after welding near the hole were higher than without it. The maximum of tensile stresses were concentrated at small areas on the edge of the hole. They are too small for experimental measuring, but they may be sufficient significant for a crack propagation or a local stress corrosion.

Wpływ lokalizacji otworu na naprężenia pozostające po spawaniu aluminium

Słowa kluczowe: spawanie, naprężenie, MES, aluminium, otwór.

Streszczenie: Podczas spawania pojawiają się niekorzystne efekty spawania (np. temperatura, strefa wpływu ciepła, naprężenia i deformacje), których występowanie w odpowiedzialnych miejscach może spowodować awarię. Aby określić strefy niebezpieczne, sprawdzano wpływ okrągłego otworu leżącego blisko wykonywanej spoiny. Zmieniając odległość krawędzi otworu, określano każdorazowo nieustalone rozkłady temperatury, wielkość jeziorka spawalniczego oraz pozostające naprężenia i deformacje. Symulowano spawanie elementu aluminiowego. Stosowano nieliniowe własności materiałowe. Użyto programu ANSYS.

Introduction

Welding is one of the basic techniques of connecting metals. To melt the metal, which make the weld, a great amount of heat is needed. The weld is heated as well as other parts of the construction. Consequently, physical changes appear, which makes the mechanical properties of metal lower. Deformation and residual stresses appear, which can be very important. They can even be dangerous for the construction. If the thickness of the material is small while the plasticity is high, there are needed significant additional loads to destroy the construction. The risk is higher for fragile materials. Thick metal sheets are in a three-dimensional (3D) stress state during and after welding. For both of those cases, the possibility of the appearance of a crack is higher. The residual deformation changes the form of construction [1, 2]. It can make their operation impossible. Shrinkage and deformation can make it difficult to keep the required tolerances. The practical ways of reducing deformations and stresses are mainly the results of a long-term experience. Technical development and the economy introduce new technologies and materials. In this case, experience cannot be sufficient.

Constructions made of aluminium alloy are lighter than made of steel. However, the welding of aluminium is much more difficult. It arises from high oxidation levels, a flatter temperature of melting, and the significant decreasing of mechanical properties $R_e(T)$. The thermal conductivity $\lambda(T)$ is about 10 times, and the thermal coefficient of expansion $\alpha_T(T)$ 2 times, higher than for steel. Often shrinkage and deformation are higher [1, 2, 3].

The occurrence of a hole near weld is often necessary. Unfortunately, the hole acts like a notch and increases the risk of damage.[4] Additionally, the hole has an influence on the temperature distribution, structure, and residual stresses after welding. It is important to check the strength of this influence. In some cases, welding near a hole triggers damages.

It is necessary to estimate the influence of the hole and its distance from the weld on residual stress at the welded elements. Regions with maximal values of residual stress can be in this case really small. Experimental evaluation can be very difficult or even impossible. For example, due to the para-magnetic character of aluminium, many methods (e.g., analyse of the Barkhausens effect) are unusable.

Even if regions with high residual stress are small, they are important and should be known during calculations of static or fatigue strength. Cracks can be initiated here, which are later able to growth in regions with a lower stress level, especially if high stress regions are lying on edge, not on the flat surface of a sheet. Stress corrosion can start in these regions [1, 2].

The temperature calculation start from Fourier--Kirchhoff heat flow equation, using the (x_0, y_0, z_0, t) coordinate system

$$div\left(\lambda gradT\right)-c_p\cdot\rho\frac{\partial T}{\partial t}=-q\left(x_0,y_0,z_0,t\right) \tag{1}$$

for an isotropic and homogeneous medium in a 3-dimensional space. With the use of ∇, this equation is as follows:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{q_V}{\lambda}=\frac{c_p\rho\partial T}{\lambda\partial t} \tag{2}$$

where
λ – thermal conductivity $Jm^{-1}s^{-1}K^{-1}$,
c_p – specific heat capacity at p =const , $Jkg^{-1}K^{-1}$,
ρ – mass density, kgm^{-3},
T – temperature, K,
t – time, s,
q_V – volumetric heat source, $Jm^{-3}s^{-1}$,
p – pressure Nm^{-2}.

Analytical solutions of (2) for welding are specific, including the geometry of objects, nonlinear thermal material properties, mobile volumetric heat sources, making the calculation difficult. With use of the FEM (Finite Elements Method) [5], it is possible to calculate a temperature field, even a time-dependent one, for many practical cases [5, 6].

Further, with Okerblom equations, ε_l which is the relative inner strain at weld is calculated with the following:

$$|\varepsilon|=\varepsilon_T-\Delta \tag{3}$$

where:
ε_T – relative thermal strain,
Δ – relative real strain.

For practical use of (3), it is necessary to set many assumptions for the simplification of material properties like independency from strain or temperature [2]. Even here, the use of the FEM gives one the possibility to find the solution, especially when temperature was previously calculated with the FEM [3, 5].

1. The numerical research

1.1. Description of FEM model

The FEM model of the welded plate (150x100x 3.8 mm) made of aluminium alloy was used here. The 2D model was lying on the surface of welded sheets. Because of the models symmetry, only ½ of the surface was calculated. Necessary thermal and mechanical restrains were set to secure symmetry conditions. Welding was simulated on a 100 mm line segment lying on the middle part of the longer symmetry line. Welding speed was set to 10 mm/s^{-1} in the X-axis direction. The weld thickness of the numerical model varied from 3.8 to 5 mm (Z axis), which correspond to thickness with the face and root of the weld.

The mesh of the elements is shown in Fig.1. The size of elements is smaller near the welding lines, because of high gradients existing here (of degrees of freedom of equations for temperature or deformation) [7]. Finite elements from the library of the program ANSYS were used: SHELL57 in thermal calculations, and PLANE42 in the structural calculations. 5996 elements with 6129 nodes were used.

The correct calculations are possible (especially for deformations and stresses) only with the use of non-linear, physical material properties that are dependent on temperature [1, 3] (Figs. 2 and 3).

The value of λ (for t>550°C) was raised from 210 to 400 $Wm^{-1}K^{-1}$, to take into account the intensive mixing of liquids in the weld pool [6].

The mechanical properties are also dependent on deformation ε. The properties are elastic-plastic, with isotropic hardening (using elastic module E, yield stress R_e, hardening module E_T). This hardening explain why values of calculated residual stress are at some cases higher then yield stress, R_e or $R_{0.2}$, obtainment from tension tests [8].

To assure numerical stability, it was necessary to set some values for material properties at non-typical temperatures, like -500°C or +5000°C. Final results of FEM calculations do not include similar temperatures.

The location of the hole has an influence on temperature and the residual stress field. A hole far away from the weld can have a negligible influence, but at a closer location, it can indicate a more significant influence. To estimate the influence of hole and its distance from weld on residual stress, 7 analyses were done; 1 without and 6 with a hole at different distances from the weld. Circular holes with

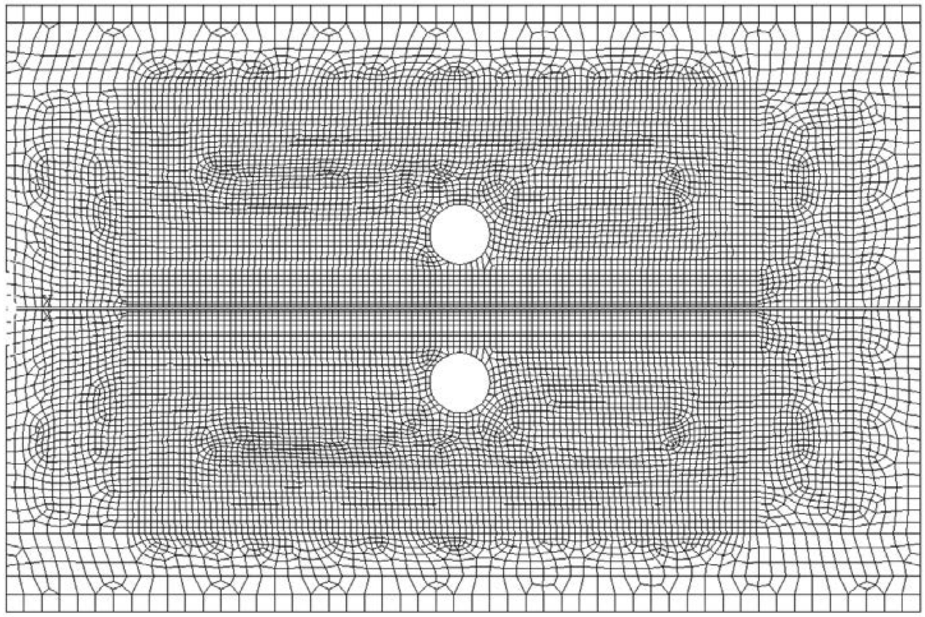

Fig. 1. Finite element mesh used in thermal and structural analysis, and results are shown for the upper half. Here b = 7 mm

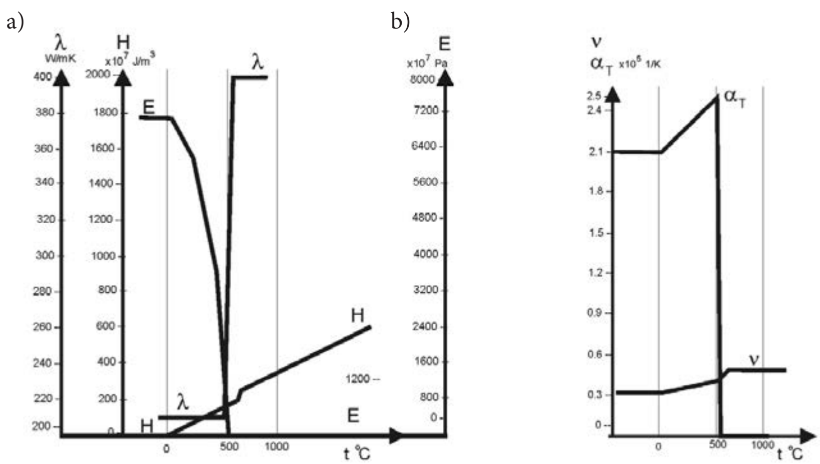

Fig. 2. Material properties, as function of the temperature: a) Specific enthalpy H, thermal conductivity λ and elastic module E; b) Poisson ratio ν, thermal dilatation α_T [1, 3]

10 mm diameter were set at localizations shown on Fig. 4. Differences on the mesh occur only near the hole. On areas important for comparison (like the weld), the mesh was constant in all 7 cases.

The volume heat source (similar to suggested by Goldak [6] for MIG/MAG) was distributed non-uniformly on 25 elements. This source was moving 1mm every 0.1 s in steps along the weld. Cumulated power, Q_o = 3.4 kW, was constant. There were welds being created in the place of grooves. It happened through completing the model by the previously removed ("killed") finite elements. On both surfaces (top and bottom), the loss of heat through convection was taken into account (20°C, air). The convection near the weld was, locally and transitorily, intensified to take into account the heat radiation, which is predominant over 600°C [3, 5].

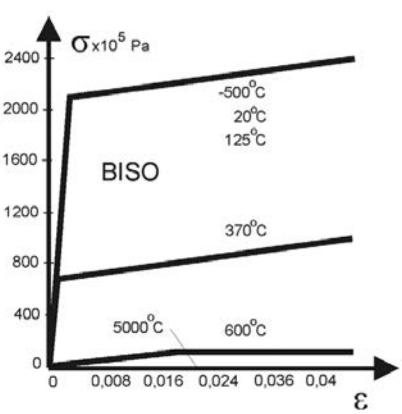

Fig. 3. Mechanical properties, elasto-plastic (Bilinear ISOtropic hardening), as a function of the temperature [1, 3]

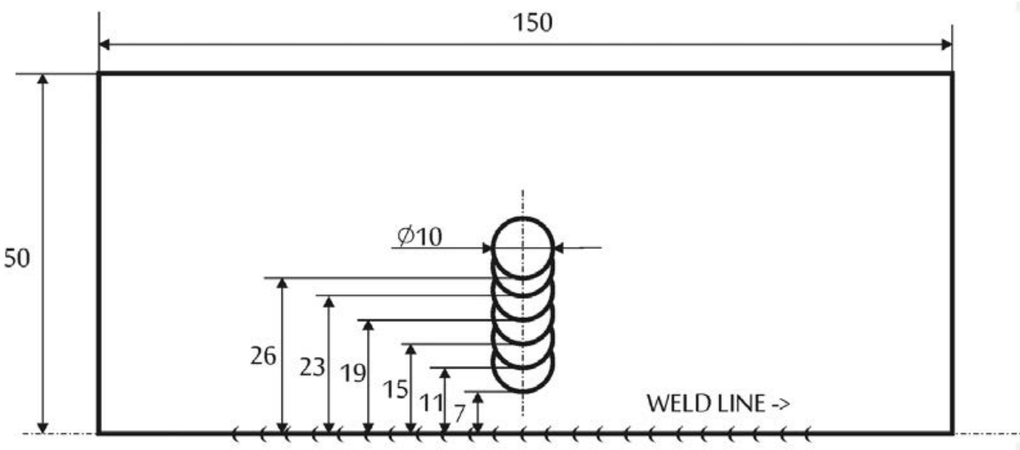

Fig. 4. Localizations of circular holes b-distance mm from weld axis, on X = 75 mm

1.2. FEM calculations

The basis of the FEM calculations were shown in [5, 6]. The calculations were done in two phases, as uncoupled thermal and structural calculations. The scheme is shown in Fig. 5, i.e. in the middle block of input data, and in the left side block of nonlinear transient thermal calculations. Its results were necessary for the right-side block of nonlinear transient structural calculations.

The FEM solution is iterative (Fig. 5) [3]. The modelling of the welding process lasted for 10.3 s, with a cooling time uniformly at 20°C for 800 s. At this time, heating (loading) and cooling of models occurred. The position of the heat source changed with the time steps mentioned above. In this way, the "step-by--step" technique was used. The results of Step (1) were necessary for the calculation of Step (2), and the results of Step (2) were necessary for the calculation of Step (3), etc. until the last step. Both of the above processes strongly (factor 10^5) lengthen the solving.

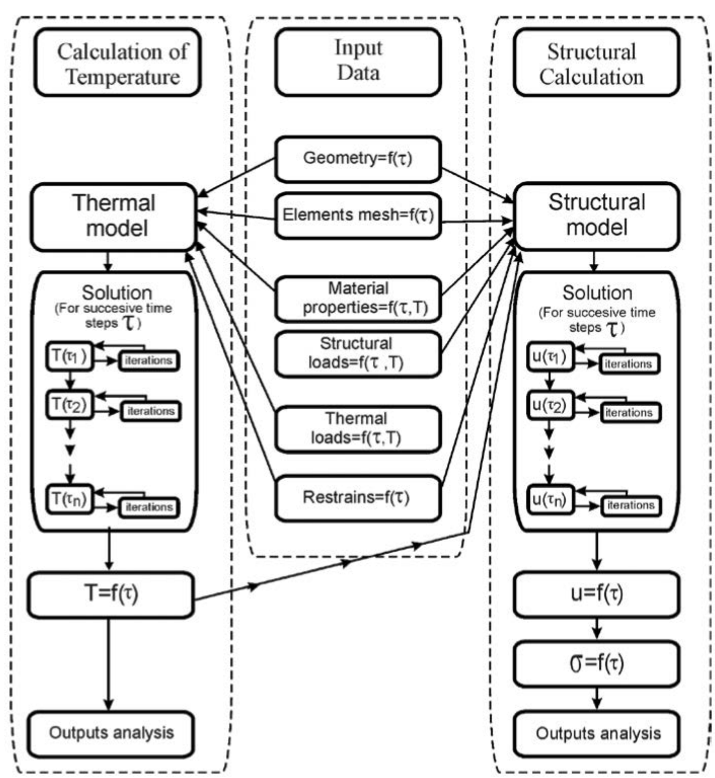

Fig. 5. Schematic diagram of transient, uncoupled thermal-structural calculations, with nonlinear material properties that are dependent on temperature [3]

Results from temperature analysis were used in stress calculations. Element types and material properties were changed to structural types. Transient and residual stresses were calculated (nonlinear, step-by--step). The used program, ANSYS, is popular among the engineers and researchers. It makes it easier to combine the calculations of strength, fatigue, optimization, etc. A physically complicated welding process inquires complicated modelling and solving procedures [2, 3, 6]. The calculation procedure was writing by the author in ANSYS APDL language.

3. Results

Firstly, the thermal steps of the FEM calculations produced a transient temperature field. The temperature field during welding at time t = 8 s for b = 7 mm is shown in Fig. 6.

Secondly, the nonlinear transient structural calculations were made. Using a large number of time steps and iterations, the residual stresses and deformations were calculated.

Table 1. Calculated residual stress (maximal values)

Hole location how on Fig. 5	Residual stress, MPa						
	Longitudinal, σ_x (global)		Longitudinal, σ_x (edge of hole)		Transverse, σ_y (global)		Transverse, σ_y (edge of hole)
	max.	min.	max.	min.	max.	min.	max.
1 (b = 7)	279	-118	279	-150	162	-198	92
2 (b = 11)	274	-168	230	-168	157	-197	125
3 (b=15)	273	-250	100	-250	157	-196	125
4 (b = 19)	273	-189	→0	-189	157	-199	80
5 (b = 23)	273	-219	→0	-219	159	-199	40
6 (b = 26)	273	-219	→0	-219	159	-199	40

Table 2. Calculated residual stress and deformation (maximal values)

Hole location how on Fig. 5	Residual stress, MPa						Deformation mm	
	Reduced (Huber-Misses)		Shear τ_{xy} (global)		Shear τ_{xy} (edge of hole)			
	(global)	(edge of hole)	max.	min.	max.	min.	(global)	(edge of hole)
1 (b = 7)	260	260	121	-109	75	-80	0.147	0.147
2 (b = 11)	245	240	121	-108	20	-100	0.156	0.13
3 (b = 15)	243	220	121	-108	→0	-100	0.145	0.13
4 (b = 19)	243	185	121	-108	→0	-100	0.135	0.13
5 (b = 23)	243	190	121	-109	→0	→0	0.135	0.12
6 (b = 26)	243	190	121	-109	→0	→0	0.135	0.13

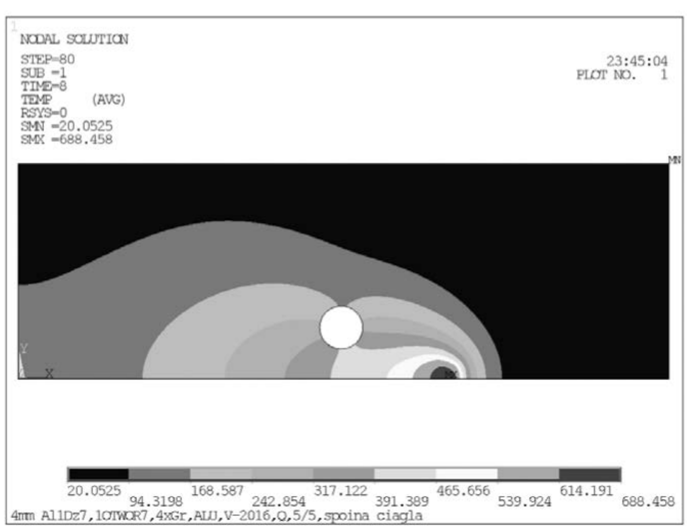

Fig. 6. Calculated temperature field, °C, during welding, at time t = 8 s, b = 7 mm

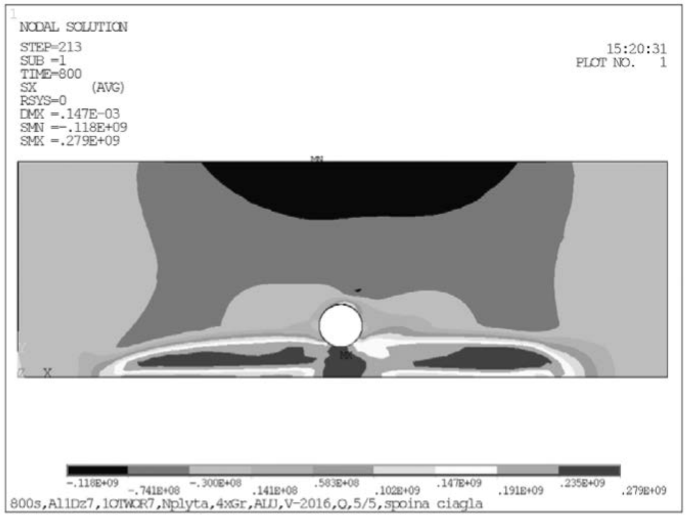

Fig. 7. Calculated longitudinal residual stress, Pa, b = 7 mm

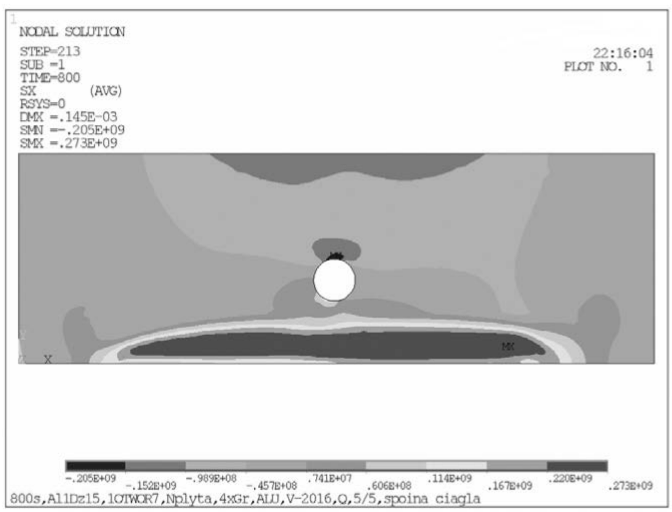

Fig. 8. Calculated longitudinal residual stress, Pa, b = 15 mm

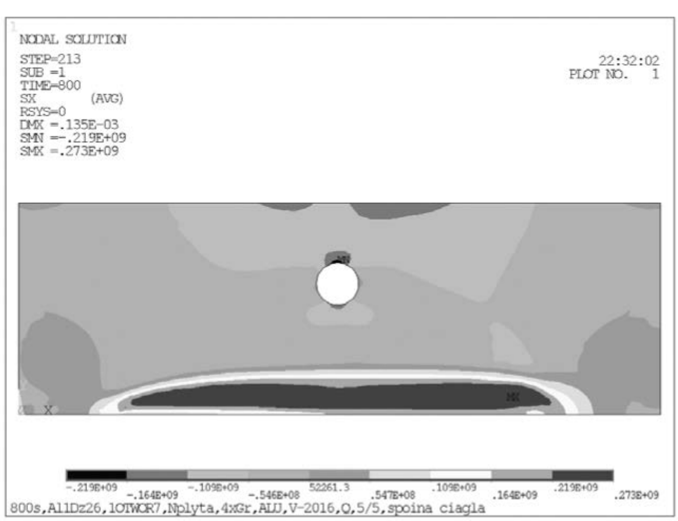

Fig. 9. Calculated longitudinal residual stress, Pa, b = 26 mm

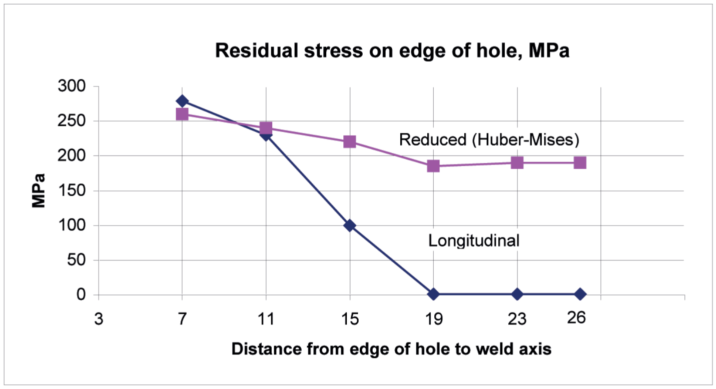

Fig. 10. Calculated residual stress as a function of distance between the edge of the hole and the weld axis

Selected results, most important for welding effects analysis, are shown in Tables 1 and 2 and in Figures 7–10. In Table 1, the maximal values of residual stress for the global model and for the edge of the hole, longitudinal and transverse, are shown. In Table 2, the maximal values of deformation and residual stress for the global model and for the edge of the hole, shear and reduced (Huber-Misses), are shown. Positive stress values can lead to the appearance of a crack, and negative values are less insecure [9, 10].

Conclusions

- The results presented in Tables 1 and 2 and Figures 7–10 show that residual stresses on the edge of the hole were significantly higher if the hole is situated closer to weld axis.
- Maximal values of tensile residual stress were concentrated in the small areas. They are too small for most methods of experimental measuring, but they can lead to opening a crack.
- Values of residual deformations were higher if the hole was closer to weld. It can change the dimensions or the location of the hole, even so much that they go beyond acceptable tolerances.
- FEM can be useful for calculation of transient and residual stresses. Values of transient stresses are very difficult to obtain in experiments.
- The application of frequently met programs like ANSYS makes it possible to practically use the suggested method of calculations, especially if the next type of analysis is slated.

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