doi.org/10.15407/tpwj2018.01.04

STRESS-STRAIN STATE OF WELDED JOINTS FROM ALUMINIUM ALLOYS UNDER THE CONDITIONS SIMULATING OPEN SPACE*

E.A. ASNIS, E.G. TERNOVOJ, E.A. VELIKOIVANENKO, A.S. MILENIN and **G.F. ROZYNKA**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

The paper gives the results of computational research of the influence of light-shade boundaries promoting preheating of joints of sunlit plates to be welded and their intensive cooling on the shaded side during electron beam welding under the conditions simulating open space, on the stress-strain state. A set of numerical procedures and software for computer modeling of the kinetics of temperature fields, stresses and strains in butt fusion welding of plates from aluminium alloy AMg6, allowing for essentially non-uniform external temperature impact were developed for this purpose. The influence of the position of light-shade boundaries relative to the weld on the forming instantaneous and residual stressed state of aluminium plates in welding was analyzed. For this purpose the respective problems of nonstationary thermoplasticity were solved by finite element method, based on computational temperature field kinetics, determined allowing for the features of the impact of welding heat source and conditions of external heating and cooling. Performed calculations showed, in particular, that distribution of residual stresses forming in welded joints of plates from aluminium alloy AMg6 at different position of light-shade boundaries, is characterized by maximum stresses, which do not reach the base metal yield limit (170–180 MPa). Such stresses should not essentially lower the mechanical characteristics and performance of welded parts and components, produced in open space conditions. 6 Ref., 3 Figures.

Keywords: *simulation of open space conditions, light-shade boundary, stressed state, mathematical modeling*

Performance of welding operations in open space can often be a necessary technological procedure in mounting and repair-reconditioning operations for critical structural elements of space vehicles in long-term operation. Selection of specific welding parameters, which guarantee the joint quality, is connected with allowing for the peculiarities of the influence of space factors (low gravity, deep vacuum, frequent change of light-shade boundaries, etc.) [1, 2]. One of the main features of welding in open space are extreme temperature variations between the shaded and illuminated part of the structure: in the sunlit section of the orbit the surface of space vehicle elements can heat up to the temperature of 120 °C, and sometimes even higher, whereas in the shaded areas the temperature drops to –100 – –120 °C [1].

Nonuniform external temperature field influences not only the welding process proper, in view of the different heat input depending on the position of light-shade boundary, but also formation of weld metal and heat-affected zone (HAZ) under the conditions of different preheating and cooling, as well as the features of structure thermal deformation.

Aluminium alloys are the main structural materials for space vehicle construction. At structure preheating up to 100–120 °C prior to welding, weld pool dimensions increase and liquid metal overcooling on the solidification front is reduced that leads to increase of the crystallite size and promotes lowering of weld strength [3]. On the shaded side metal resistance to solidification crack formation can decrease, because of low temperatures, although lowering of initial temperature has practically no influence on weld metal mechanical properties [4]. Arising stresses in welded joints can further influence lowering of hot cracking resistance of weld metal and can lead to deterioration of structure performance that is particularly important at long-term operation of space vehicles.

In view of a quite limited number of welded samples, produced in open space and delivered to Earth [1], no investigations of their stress-strain state (SSS) were conducted. As experimental evaluation of the influence of open space conditions on welded joint SSS involves objective difficulties, application of mathematical and computer modeling methods is the rational approach.

*Participated in work performance S.A. Glushak, T.A. Likarenko.

The objective of this study consisted in numerical analysis of peculiarities of SSS in a butt welded joint produced under the conditions simulating open space, at different position of light-shade boundary.

A set of mathematical models and tools for their computer implementation was developed, which allow solving joint tasks of temperature field kinetics under the impact of a rapidly moving welding heat source, and spatially nonuniform field of ambient temperatures. Development of stresses and strains was assessed in butt welded plates (plane stressed state, Figure 1). Solved for this purpose was the problem of nonstationary heat conductivity for temperature field $T(x, y)$ under the impact of a welding heat source of power W:

$$\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T(x,y)}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T(x,y)}{\partial y}\right)+ +W=c\gamma(T)\frac{\partial T(x,y)}{\partial t}, \quad (1)$$

where $\lambda(T)$ is the coefficient of thermal conductivity; $c\gamma(T)$ is the bulk heat capacity; t is the current moment of time.

Proceeding from the features of surface heat removal in open space environment, boundary conditions to equation (1) were formulated as follows:

$$-\lambda(T)\frac{\partial T(x,y)}{\partial n}=\varepsilon\sigma_{SB}\left(T^4-T_C^4(x)\right), \quad (2)$$

where

$$T_C(x)=\begin{cases}T_{\text{sh}}, \text{если } x<x_0,\\ T_{\text{sn}}, \text{если } x\ge x_0,\end{cases} \quad (3)$$

where T_{sh}, T_{sn} is the ambient temperature on the shaded and sunlit sides of the structure, respectively; ε is the degree of blackness of the surface of the structure being welded; σ_{SB} is the Stephan–Boltzmann constant; x_0 is the current position of light-shade boundary; n is the normal to the surface.

Prediction of residual stresses was performed using a calculation procedure, based on consistent tracking of development of elasto-plastic deformations in points x, y on sample cross-section during heating in welding and subsequent cooling [5]. So, at any moment of time t strain tensor ε_{ij} can be represented as a sum of tensors:

$$\varepsilon_{ij}=\varepsilon_{ij}^e+\varepsilon_{ij}^p+\varepsilon_{ij}^T, \quad (4)$$

where ε_{ij}^e is the tensor of reversible elastic deformations; ε_{ij}^p is the tensor of nonelastic deformations of instant plasticity; ε_{ij}^T is the tensor of reversible temperature deformations.

Thus, we will represent incremental strain tensor $\Delta\varepsilon_{ij}$ at each tracking step as follows:

$$d\varepsilon_{ij}=d\varepsilon_{ij}^e+d\varepsilon_{ij}^p+\delta_{ij}\left(d\varepsilon_{ij}^T\right), \quad (5)$$

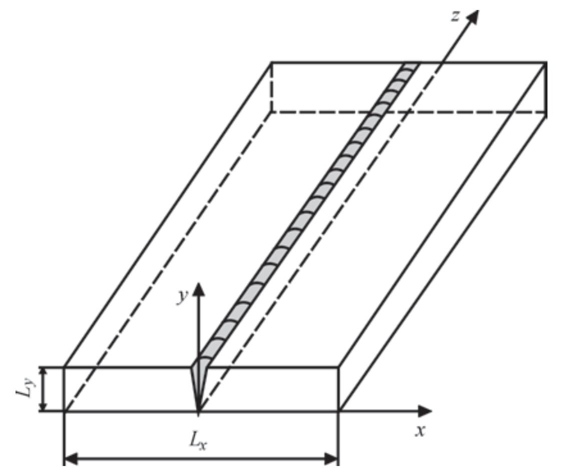

Figure 1. Schematic of sample welding

where δ_{ij} is the unit tensor or Kronecker symbol, i.e. $\delta_{ij}=1$ at $i=j$ and $\delta_{ij}=0$ at $i\neq j$.

The connection between stresses σ_{ij} and strain increments in point (x, y) at moment of time t, compared to $t = 0$, is determined by generalized Hooke's law, allowing for volume temperature and microstructural changes 3φ and associated law of plastic flow:

$$\Delta\varepsilon_{ij}=\psi\left(\sigma_{ij}-\delta_{ij}\sigma\right)+\delta_{ij}\left(K\sigma+\Delta\varepsilon_{ij}^T\right)- -\frac{1}{2G}\left(\sigma_{ij}-\delta_{ij}\sigma\right)^*-\left(K\sigma\right)^*, \quad (6)$$

where ψ is the function of the state of elasto-plastic material, determining the degree of plastic flow development; $\sigma=(\sigma_{xx}+\sigma_{yy}+\sigma_{zz})/3$, $G=E/2(1+\upsilon)$ is the shear modulus; E is the modulus of normal elasticity; υ is the Poisson's ratio; $K=(1-2\upsilon)/E$ is the modulus of bulk compression.

Function ψ reflects the state of material in point x, y at moment of time t: it is either equal to $1/2G$ (elastic behaviour), or is greater than $1/2G$ (elasto-plastic behaviour). Yield condition allows constructing the iteration process of refining function ψ:

$$\begin{aligned}&\psi=\frac{1}{2G}, \text{ if } \sigma_i<\sigma_s=\sigma_T(T);\\ &\psi>\frac{1}{2G}, \text{ if } \sigma_i=\sigma_s;\\ &\text{state } \sigma_i>\sigma_s \text{ is unacceptable,}\end{aligned} \quad (7)$$

where σ_y is the material yield point; σ_i is the stress intensity.

Without loss of generality, a typical flat welded sample from aluminium alloy AMg6 with dimensions $L_z \times L_x \times L_y = 180\times50\times2$ mm was considered for calculations, that corresponds to samples produced in space. Electron beam butt welding was performed. Welding modes were as follows: accelerating voltage U_{acc} = = 10 kV, beam current I_{b} = 100 mA, welding speed v_{w} = 8 mm/s. Depending on the position of light-shade boundary x_0 relative to welded joint line, the following welding conditions were considered:

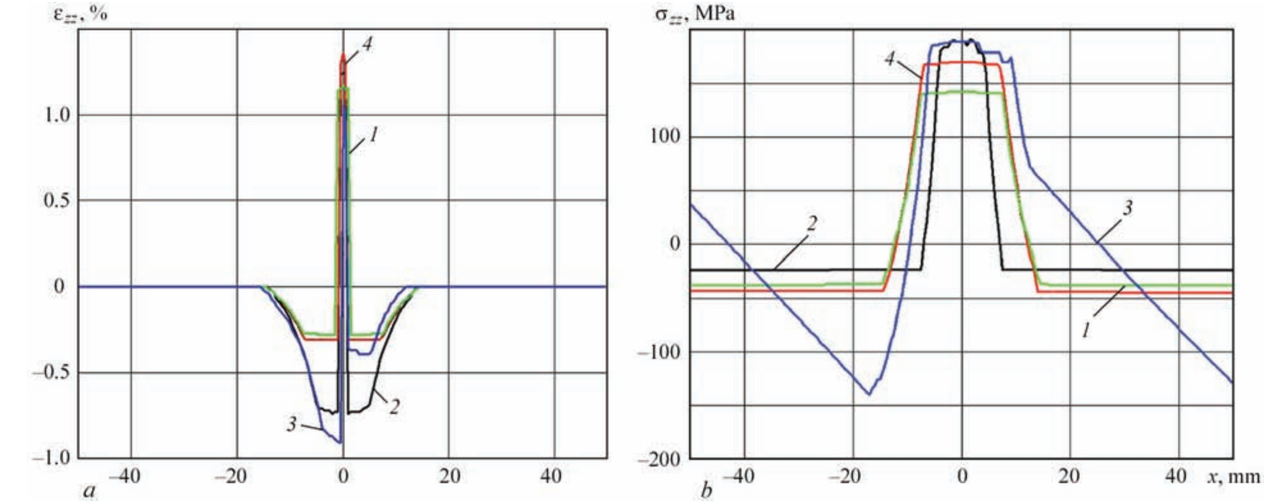

Figure 2. Distribution of residual longitudinal deformations ε_{zz} (*a*) and stresses (*b*) across the sample width at different conditions of external temperature impact: *1* — on sunlit; *2* — on shaded side; *3* — at light-shade boundary position on the butt being welded (x_0 = = 0), when one of the plates being welded is heated up to temperature T_{sn} = 120 °C (positive 0*x* half-axis), and the other is cooled to T_{sh} = –120 °C (negative 0*x* half-axis); *4* — ambient room temperature (20 °C)

1. Welding on the sunlit side ($x_0 < -L_x/2$), i.e. with preheating up to the ambient temperature $T_{amb} = T_{sn}$ = = 120 °C.

2. Welding on the shaded side ($x_0 > L_x/2$), i.e. with cooling to ambient temperature $T_{amb} = T_{sh}$ = –120 °C.

3. Welding at light-shade boundary position on the butt to be welded (x_0 = 0), when one of the plates being welded is heated up to temperature T_{sn} = 120 °C, while the other one is cooled to T_{sh} = –120 °C.

SSS of the sample of the above dimensions after welding at room temperature (20 °C) was also calculated for comparison.

Calculations showed that transverse stresses σ_{xx} and deformations ε_{xx} have very low values, close to zero, and, that is why they are not considered further-on. Processes of irreversible deformation shrinkage in the area of local heating in welding determine formation of high longitudinal deformations ε_{zz} and stresses σ_{zz} that is characteristic for welding plates [6]. So, magnitude of deformations ε_{zz} does not exceed 1.5%, depending on temperature conditions on the boundary of the item being welded. Here, at nonuniform heating (condition 3) differences in the properties of plates being welded and heating/cooling conditions cause a slight increase of longitudinal shrinkage deformations in the structure shaded side, while total deformations remain within the generally accepted tolerances (Figure 2, *a*).

Figure 2, *b* gives the curves of residual longitudinal stresses σ_{zz}. The highest values were observed in the weld, and they practically do not differ from each other, depending on ambient temperature conditions: the differences depend on the difference in material yield points at the respective temperatures. A characteristic feature of the stress field at nonuniform heating (condition 3) are nonzero values of stresses

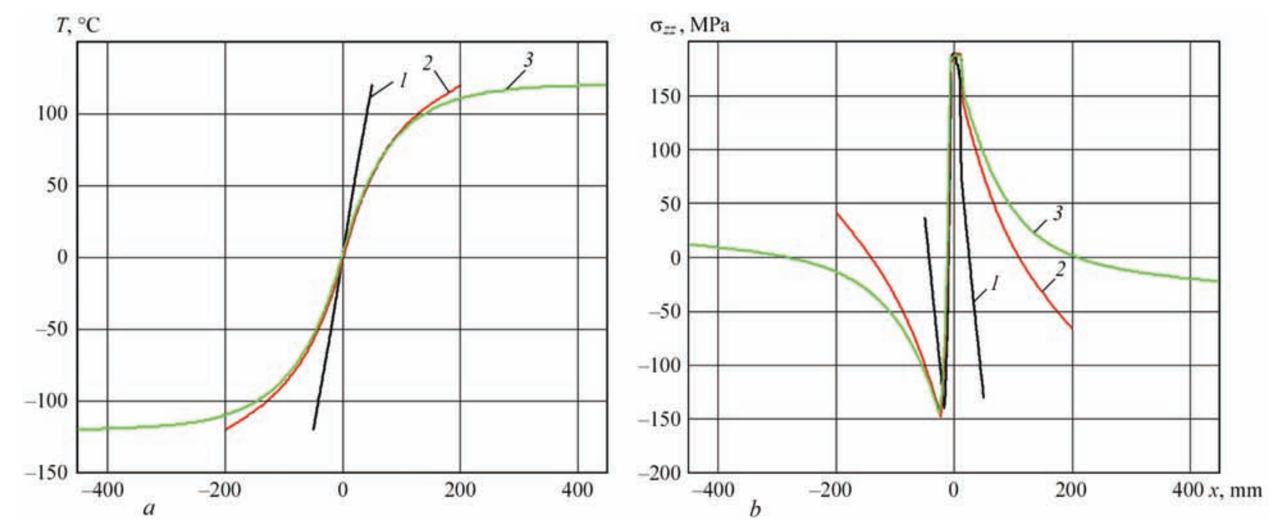

Figure 3. Influence of the width of sample being welded L_x on distribution of temperature (*a*) and longitudinal residual stresses σ_{zz} (*b*) provided the light-shade boundary is located along the weld: *1* — L_x = 100 mm; *2* — 400; *3* — 900

on sample periphery. This is associated with the fact that despite the presence of light-shade boundary on the surface of the item being welded, the temperature is distributed across the metal thickness according to metal physical properties (heat conductivity and heat capacity), so that transition from temperature T_{sh} = = –120 °C to T_{sn} = 120 °C is smooth (Figure 3, *a*). The width of the considered sample is such that the temperature gradient is preserved across its entire section, leading to formation of the respective balanced stresses. Increase of sample width neutralizes the impact of temperature gradient in the area of light-shade boundary on the stressed state on its periphery (Figure 3, *b*).

Conclusions

1. Calculation results showed that preheating and cooling do not affect the SSS of welded joints of aluminium alloy AMg6.

2. Stresses in welded joints do not exceed base material yield point. Such stresses do not have any essential influence on strength properties and performance of welded joints produced in space environment.

3. Results of numerical studies were used to demonstrate the influence of the width of butt-welded sample from aluminium alloy AMg6 on temperature and stress distribution at its nonuniform heating under the conditions simulating open space. It is shown that presence of a light-shade boundary (with temperature range from –120 °C to 120 °C) leads to formation of a transition region in the metal of about 400 mm length. Therefore, in welding smaller-sized samples stress distribution is characterized by increase of the longitudinal component relative to the item periphery.

1. Paton, B.E. (2000) *Space: technologies, materials science, structures*. Kiev, PWI [in Russian].
2. Fragomeni, J.M., Nunes Jr., A.C. (2003) A study of the effects of welding parameters on electron beam welding in the space environment. *Aerospace Sci. and Technology*, **7**, 373–384.
3. Rabkin, D.M. (1986) Metallurgy of welding of aluminium alloys. Kiev, Naukova Dumka [in Russian].
4. Bondarev, A.A., Ternovoj, E.G. (2010) Features of weld formation and properties of aluminium and magnesium alloy joints under simulated space conditions. *The Paton Welding J*., **11**, 16–20.
5. Makhnenko, V.I. (2006) *Resource of safe operation of welded joints and assemblies of modern structures*. Kiev, Naukova Dumka [in Russian].
6. Mi, G., Li, C., Gao, Z. et al. (2014) Finite element analysis of welding residual stresses of aluminum plates under different butt joint parameters. *Engineering Review*, 34(**3**), 161–166.

Received 20.11.2017