E. KANNATEY-ASIBU JR.*, W. WŁOSIŃSKI**, A. KRAJEWSKI***

NEW METHOD OF SOLID-STATE JOINING THIN-WALL ELEMENTS MADE OF ALUMINUM ALLOYS

NOWA METODA SPAJANIA W STANIE STAŁYM CIENKOŚCIENNYCH ELEMENTÓW ZE STOPÓW ALUMINIUM

The paper presents a new method of fabrication by joining, in the solid state, thin-wall rectangular tube used in heat exchangers (e.g. automobile radiators). The heat transfer during the joining operation with the use of form rolls was analyzed by thermal calculations and numerical modeling. At present, products of this type are usually joined by induction heating. The joining rate amounts here to several meters/min, but this technique is highly energy-consuming and requires a large floor area. The proposed method eliminates these drawbacks. The heat source is here a plasma arc ignited using an Ultima 150 device. The results of an analysis of the heat phenomena and their numerical modeling presented in the paper constitute the preliminary stage of studies on the implementation of this new method. .

Zaprezentowano innowacyjną metodę spajania w stanie stałym do wykonywania prostokątnych rur cienkościennych znajdujących zastosowanie w budowie wymienników ciepła (np. chłodnice samochodowe). W artykule przedstawiono podejście modelowe do przepływu ciepła podczas łączenia przy użyciu rolek kształtowych. Obecnie w przemyśle powszechnie stosuje się zamykanie tego rodzaju profili wykorzystując nagrzewanie indukcyjne. Prędkość łączenia dochodzi do kilku m/min, jednakże sposób ten cechuje duże zużycie energii i znaczne zapotrzebowanie powierzchni produkcyjnej. Zaproponowana metoda redukuje te niedogodności. Jako źródło ciepła zastosowano łuk plazmowy przy wykorzystaniu urządzenia Ultima 150. Przedstawione wyniki modelowania i badań to początkowy etap prac nad implementacją tej metody, który obejmuje analizę zjawisk termicznych i ich modelowanie numeryczne.

1. Introduction

One of the principal problems encountered in the fabrication of heat exchangers lies in how to join thin walls so that the joints are tight and that the costs of the process are low and its efficiency was high. The quality of the joints depends on many factors such as [1]:

- limited wettability between the materials to be joined since they may differ in their chemical compositions and structures which may e.g. be due to plastic treatment they were subjected to,
- the state of the external surfaces of the tubes (roughness, cleanliness, oxidation degree, etc),
- type of anisotropy of their structure,
- cleanliness of the two surfaces to be joined in the immediate vicinity of the joint,
- method of joining, monitoring and controlling the operational parameters, the possibility of optimizing these parameters, and the reproducibility of the qualitative properties of the joints,
- synchronization of the thermal processes with the moment of application of the force,
- mechanical, thermal and chemical treatments applied after the joining process, and
- conditions prevailing during storage, transport, exploitation and servicing of the joints.

The good thermal conductivity, high corrosion resistance and low density are the reasons why aluminum alloys and, increasingly, composites of these alloys are used for the fabrication of heat exchangers. These materials are however very sensitive to the action of concentrated heat fields. Some of them are liable to hot cracking.

It follows from industrial practice that the surface of aluminum parts is covered with a quite thick layer of oxides or, sometimes, of organic substances left

* UNIVERSITY OF MICHIGAN, MECHANICAL ENGINEERING, COLLEGE OF ENGINEERING, 2350 HAYWARD ST., ANN ARBOR, MI 48109-2125 USA
** POLISH ACADEMY OF SCIENCE DIVISION IV TECHNICS SCIENCES
*** WARSAW UNIVERSITY OF TECHNOLOGYFACULTY OF PRODUCTION ENGINEERING, 85 NARBUTTA ST., 02-524 WARSAW, POLAND

after plastic treatment. This can make the joining operation difficult and can degrade the quality of the joints. Moreover, the heavy squeeze suffered during the rolling operation results in a strong anisotropy of the structure and mechanical properties of the aluminum sheets.

In industry, thin-wall parts are commonly joined by induction welding. However, the operational costs of induction generators are very high, because chiefly of the high energy consumption. Moreover, to be installed these generators require a large surface area. This is why other less expensive techniques of heat delivery into the region of the joint are being sought.

To fulfill the requirement of economic efficiency, the alternative method should ensure the same joining rate as that achieved at the present, i.e. about 1 m/s.

Classical techniques of joining thin composite walls (e.g. GTA) may result in delamination of the individual composite layers and the occurrence of numerous discontinuities, such as perforation, porosities, undercutting or incomplete penetration.

In view of these problems it is not easy to choose an appropriate joining method such that would guarantee the reproducibility of the joint quality. This is why attempts have been made to combine two or more techniques, i.e. to try a sort of the hybrid technique that utilizes the essential factors advantageous for the fabrication of joints but avoids the disadvantages of the conventional methods. This, obviously, is a technological and investment challenge, which not always can be undertaken because of time consumption and cost reasons. In order to avoid the expensive try-and-error method, it is reasonable to analyze first the thermal phenomena that occur in the joining operation and to construct a numerical model. The present paper presents some selected results of a new technique that combines the classical fusion welding method with diffusion-aided joining in the solid state.

2. Experimental

2.1. Materials

The material used for the fabrication of thin-wall tubes is a three-layer composite made of two different aluminum alloys. The structure of this composite is shown in Fig. 1. The chemical composition and properties of its constituent aluminum alloys are given in Table 1.

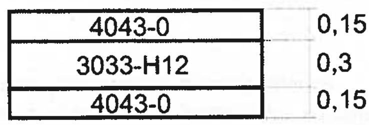


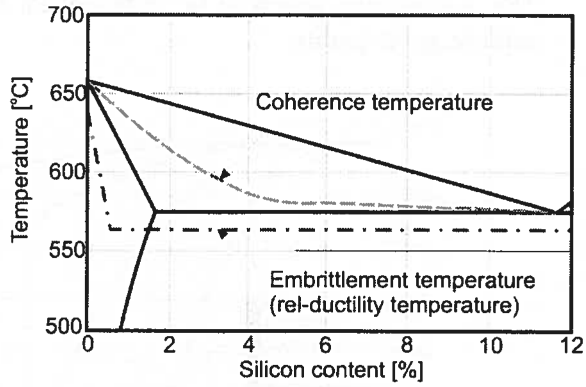
Fig. 1. Cross-section of the composite built of aluminum alloys intended for the fabrication of vehicle radiators

TABLE 1

Properties of the 3003-H12 and 4043-0 aluminum alloys used for the fabrication of the three-layer composites

ρ kg/m^3	R_m MPa	R_e MPa	E GPa	A %	c J/kgK	γ J/mK	a m^2/s	T_L/T_S (°C)	ϵ
3003-H12 (wt %): Al 98,7; Cu 0,05÷0,2; Fe max 0,7; Mn 1÷1,5; Si max 0,6; Zn max 0,1									
2730	130	125	69	10	893	162	6,65 10^{-5}	643/654	0,038-0,33
4043-0 (wt %) Al: 94,8; Cu max 0,3; F max 0,8; Mg max 0,05; Mn max 0,05; Si: 4,5÷6; Ti max 0,2; Zn max 0,1									
2680	145	70	69	22	850	163	7,16 10^{-5}	574/632	0,038-0,33
ρ – density, R_m – ultimate tensile strength, R_e – yield strength, E – Young modulus, A – elongation, c – specific heat, λ – thermal conductivity, a – thermal diffusity, T_L/T_S – temperature of liquidus/solidus, ϵ – emissivity									

It is worth noting that, because of the silicon present in the aluminum alloys, cracks may occur during crystallization. How silicon affects the properties of the Al-Si alloy is illustrated in Fig. 2a. Fig.2b shows the variation of the mechanical properties of the Al-Si alloy (1% of Si) as a function of temperature. We can see that above a certain temperature the alloy becomes brittle.



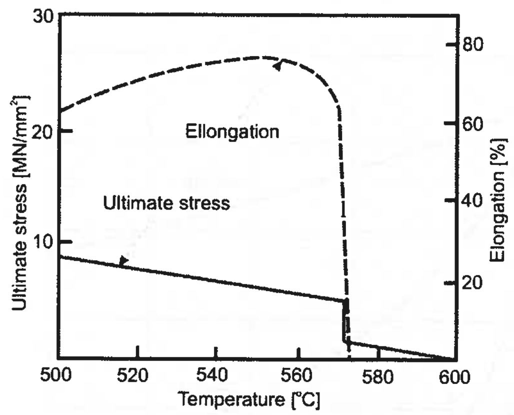


Fig. 2. Effect of the silicon content upon the properties of the Al-Si alloy: (a) Al-Si phase diagram indicating the temperature at which, during cooling, the alloy becomes brittle, (b) Mechanical properties of the aluminum alloy with a 1% silicon content [3]

Based on these properties of the Al alloys we can draw a very important conclusion that, because of the danger of brittleness, the temperature at which the aluminum tubes are joined should not exceed 833K (560°C). The joining temperature must not however be lower than 673K (400°C) so as to permit diffusion in the solid state to proceed, since it is necessary for achieving a good continuous joint between the thin walls of the tubes [4].

2.2. Joining technique

The idea underlying the proposed joining technique is to deliver the desired heat flux to the specified region of the tubes to be joined. The joining region is spaced by about the distance Z from the axis of the pressing force (Fig. 3). The crucial job here is to determine the optimum process parameters (distance Z, the amount of the delivered heat Q, and the tube traveling speed v), such that the joining process proceeds within the temperature range from 673K (400°C) to 833K (560°C).

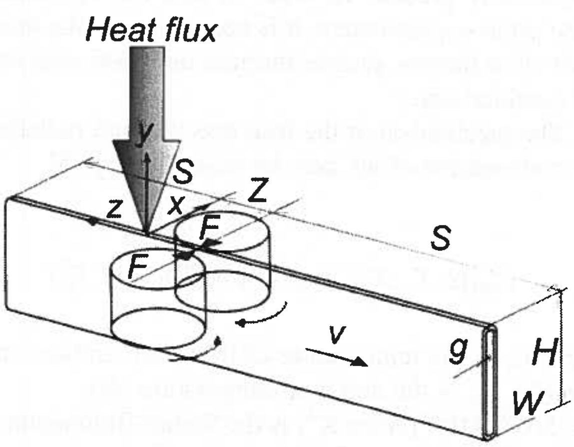


Fig. 3. Idea underlying the joining process: F – pressing force, v – travel speed of the tube (joining rate), g – thickness of the tube wall (0,6mm), H – height of the (25,4mm), W – width of the tube (5mm), x, y, z – coordinates, Z – distance between the axes of the pressing rolls and the axis of the concentrated heat source

The joining process should thus proceed through diffusion in the solid state, without the occurrence of the liquid phase. The only role of the plasma arc consists of heating the joint area to the required temperature.

2.3. Analysis of the heat distribution

The dependence of the maximum temperature T_p that prevails during the action of the heat source which moves at the velocity v (tube traveling speed) and the heat Q introduced into the system on the distance Z at which the concentrated heat source is installed has been described by empirical equation [5] to be

$$\frac{1}{T_P - T_0} = \frac{4.13\rho c g Z v}{Q} + \frac{1}{T_m - T_0} \quad (1)$$

where T_p [K] is the maximum temperature at the distance Z [m] from the heat source, T_m [K] is the melting temperature of the materials being joined, T_0 [K] is the ambient temperature, v [m/s] is the traveling velocity of the heat source, ρ[kg/m^3] is the density of the materials, c [J/kgK] is the specific heat, Z [m] is the distance from the heat source measured perpendicularly to the velocity vector.

Using this relationship we can calculate the maximum temperature T_p:

$$T_p = \frac{QT_m + 4.13cg(T_m - T_0)T_0 vZ\rho}{Q + 4.13cg(T_m - T_0)vZ\rho} \quad (2)$$

The calculation results obtained for various values of the travel speed v are shown in Fig. 4.

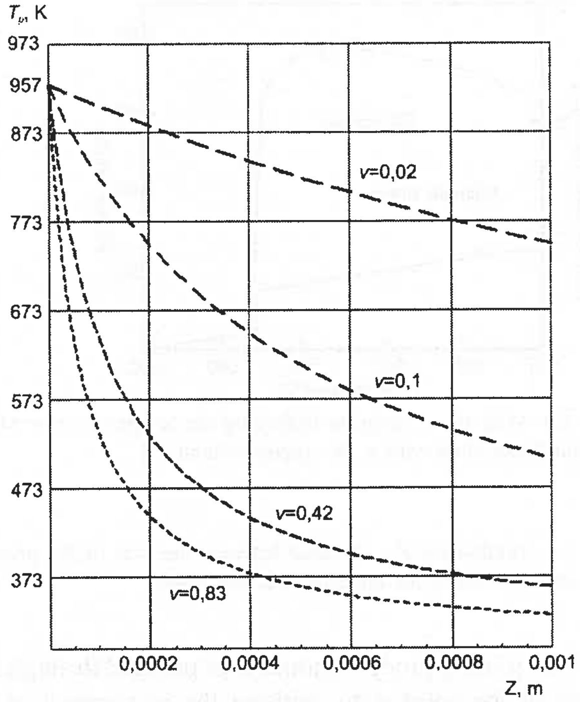


Fig. 4. Variation of the maximum temperature T_p as a function of the distance Z at various velocities v [m/s]; Q = 3255W, T_m = 927K (654°C), T_0 = 293K (20°C)

We can see from Fig. 4 that, within the velocity range (v) from 0,42 to 0,83 [m/s] and the temperature range (T_p) from 673 to 833K, the distance Z does not exceed 0,00005m (0,05mm).

Let us now consider the cooling rate C_R [K/s]. According to Adams [5] it may be calculated from the relationship

$$C_R = -2\pi\rho c(\frac{gv}{Q})^2(T_c - T_0)^3 \quad (3)$$

where T_c [K] is the temperature from which the material is cooled, T_0 [K] is the temperature of the ambience. The results of the cooling rate analysis are shown in Fig. 5.

It follows from Fig. 5 that, when the temperature T_c is equal to the melting temperature T_m, the values of the cooling rate C_R are very high and even exceed 10000K/s. Another observation is that at the ambient temperature T_0 ranging from 293 to 473K (20-200°C) and the joining rate v=0,83m/s, the cooling rate varies from 6000K/s even to above 10000K/s.

Let us perform some simple exemplary calculations.

Assuming that v=0,42m/s, T_0 = 293K (20°C) and $Z = 0,01$m, then the time necessary for the tube to move to the region of action of the clamping forces will be t=(Z/nu)=0,024s. During this time, the tube will be cooled by $\Delta T = C_{Rt} = 4100 \times 0,024 = 98$K (°C). Assuming further that $T_c = T_m$ = 927K (654°C), the temperature T_b of the tube when it reaches the joining region will be $T_b = T_c + \Delta T = 654 - 98 = 829$K (556°C).

This temperature seems to be sufficient for the joint to achieve good quality.

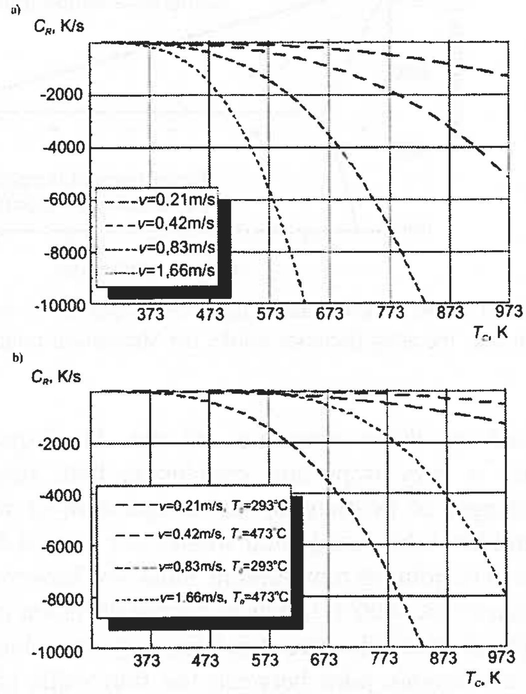


Fig. 5. Relation between the cooling rate C_R and the temperature T_C at various values of v at Q = 3225W and (a) T_0 = 293K (20°C), (b) T_0 = 293-473K (20-200°C)

If we increase the traveling velocity v to 0,83m/s and T_0 to 473K (200°C) at $Z = 0,01$m, then $t = 0,012$s and $\Delta T = C_{Rt} = -6000 \cdot 0,012 = -72K$ (°C). Hence $T_b = T_c + \Delta T = 927 - 72 = 855$K (582°C), a temperature which may be too high for the aluminum alloy to avoid its transforming into the brittle state.

The analysis given above permits estimating the relation between the cooling rate, the initial cooling temperature and the ambient temperature, but it does not describe the temperature distribution which would be satisfactorily precise. In order to find the optimum set of the process parameters, it is necessary to take into account other factors, such as thermal radiation, convection and conductivity.

The mechanism of the heat loss through radiation in the environment of air may be described by [5]

$$h_{rad}\{\varepsilon, T_w, T_0\} = \varepsilon\sigma(T_w + T_0)(T_w^2 + T_0^2) \quad (4)$$

where T_w is the temperature of the outer surfaces of the tube [K], T_0 is the ambient temperature [K], $\sigma = 5,670410^{-8}$[W/m^{2}K^4] is the Stefan-Boltzmann constant, and ε is the emissivity.

The results of this analysis are shown in Figs 6 and 7.

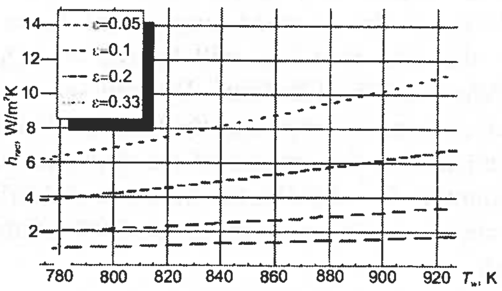


Fig. 6. Variation of the radiation heat-loss coefficient hrad as a function of the tube surface temperature T_w at various values of the emissivity ε; T_0 = 293K (20°C)

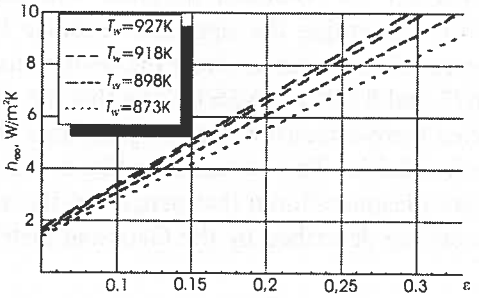


Fig. 7. Variation of the radiation heat-loss coefficient hrad as a function of the emissivity ε at various tube surface temperatures T_w; T_0 = 293K (20°C)

The natural convection in air is described by the empirical equation [6]

$$h_{conv}\{B, T_w, T_0\} = 0,42\frac{\sqrt[4]{T_w - T_0}}{B} \quad (5)$$

where B is a characteristic surface dimension representing the distance from the heat source beyond which the temperature increase during the joining operation is insignificant

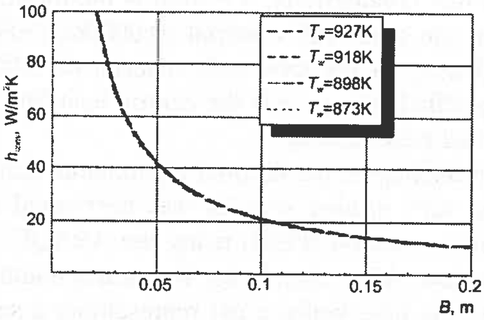


Fig. 8. Variation of the convection heat-loss coefficient h_{conv} versus the characteristic dimension B at various temperatures T_w; T_0 = 293K (20°C), $\varepsilon = 0,2$

Natural convection predominates below a temperature of 823K (550°C), whereas radiation begins to predominate above this temperature. The variation of the convection heat-loss coefficient depending on the characteristic surface dimension B is shown in Fig. 8.

The coefficient of the total heat loss h_{total} [W/m^{2}K], which represents both heat radiation and convection from the outer surfaces of the tubes, is the sum of h_{conv} and h_{rad} [7]. Graphical representations of the variation of h_{total} as a function of various process parameters are given in Figs 9 to 12.

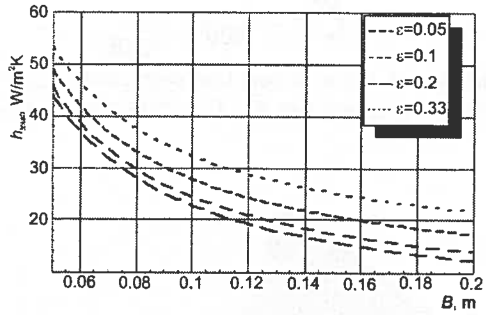


Fig. 9. Variation of the total heat-loss coefficient h_{total} with the temperature T_w; T_0 = 293K (20°C), B=0,2m

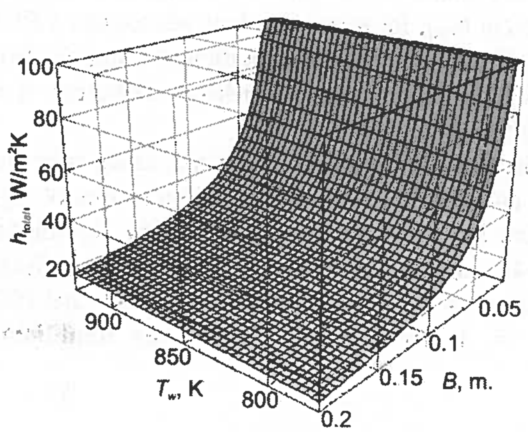


Fig. 10. Variation of the total heat-loss coefficient h_{total} and the sur-

face dimension B with the emissivity ε; T_w = 927K (654°C), $T_{0=293}$K (20°C)

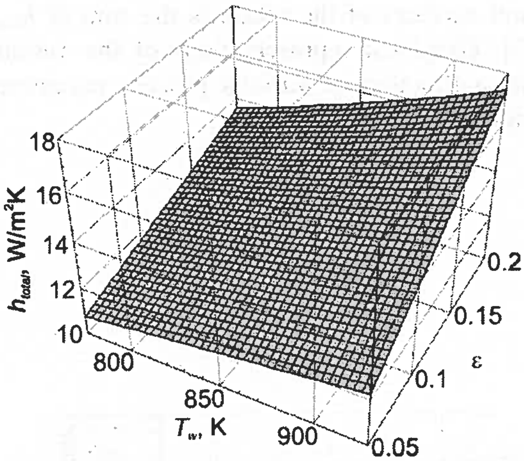


Fig. 11. Variation of the total heat-loss coefficient h_{total} with the emissivity ε and the temperature T_w; T_0 = 293K (20°C), $B = 0,2$m

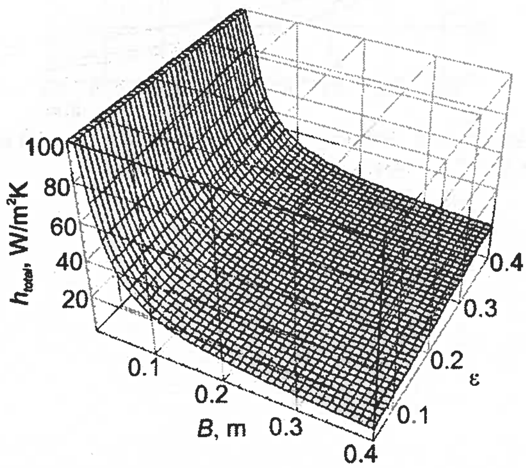


Fig. 12. Variation of the total heat-loss coefficient h_{total} with the emissivity ε and the surface dimension B; T_0 = 293K (20°C), T_w = 927K (654°C)

In the case considered, the heat-loss due to convection and radiation is insignificant. The radiation heat-loss coefficient h_{rad}, for example, does not exceed 12W/m^{2}K, and with the convection coefficient ranging from 10 to 100W/m^{2}K, the total heat-loss coefficient is below 112W/m^{2}K.

The heat-dissipating surface area of the tube can easily be calculated. Assuming the dimensions of fig.3 the effective length of the tube $Z = 0,02$m, its height W = 0,0254m and width t = 0,005m, the heat-dissipating surface area is $S = 2(0,02 \cdot 0,005) + 2(0,00254 \times 0,02) = 1.216 \cdot 10^{-3}$m^2. Hence the total heat loss is $\Delta Q_R = h_{total} S = 112$W/m^{2}K$\cdot 1,216 \cdot 10^{-3} m^2$ = 0,1362W/K. At the assumed temperature T_m = 927K (654°C), the total heat loss will be $\Delta Q = \Delta Q_R T_m$ = 0,1362W/m^{2}K·927K=126W/m^2. We can see that even with such extreme assumptions, the heat loss is insignificant compared to the amount of the delivered heat Q. If, for example, Q = 3255W, the heat loss of 126W, calculated above, constitutes only about 3,9% of the heat delivered.

2.4. Numerical model of the joining process

These calculations formed the basis for constructing a numerical model of joining the tube walls with the use of the ABAQUS 5.8 computer program. The principal goal was the determine the optimum distance Z from the concentrated heat source where the temperature falls between 673 and 833K (400-560°C) so that the pressing force applied there can ensure that the joint thus obtained is tight and reliable. The concentrated heat flux, taken to be the arc plasma column that penetrates the walls of the tubes, can be described by the Gaussian distribution [8]

$$q = q_0 e^{(-CR^2 - \frac{\beta v}{2a} w)} \tag{6}$$

where $q_0 = \frac{QC}{\pi} C = \frac{4L_{arc}(\frac{1}{1-F})}{D^2}$ $R = \sqrt{\frac{100 L_{arc}}{C}}$, L_{arc} is the length of the electric arc (0,003m), F is the degree of heat energy concentration on the outer surface of the tube walls (0,99), D is the effective diameter of the arc plasma column (0,001m), C is a shape constant (0,001m^{-1}), β is a constant ($\beta = 0$ corresponds to the undistorted ideal normal heat distribution), R is the radius of the arc cross-section measured on the outer surface of the tube calculated from the arc axis, v[m/s] is the traveling speed of the tube, $w = vt$[m] is the coordinate of the movement, t[s] is the time of the action of the arc, λ = 162W/mK is the thermal conductivity, $a = \lambda/c\rho$ is the thermal diffusivity of the tube wall material (0,0000664509m^2/s), ρ is the density of the tube wall material (2730kg/m^3), c is its specific heat, $q - o$ is the central heat flux of the concentrated heat source.

The modeling of the thermal phenomena that occur during the tube joining process was performed by the finite element method (FEM) using the ABAQUS computer program. After calculating the heat amount introduced into the tube walls, a net representing a segment of the tube was prepared. The definitions and assumptions adopted in the ABAQUS program modeling were [9, 10]:

$$\text{Energyequation(Green – Naghdiequation)}: \int_V \rho \dot{Q} dV = \int_S q dS + \int_V r dV \quad (7)$$

$$\text{Constitutiveequation}: c(T) = \frac{dQ}{dT} \quad (8)$$

$$\text{Boundaryconditions}: T = T(x, y, z, t) \qquad q = q(x, y, z, t) \quad (9)$$

$$\text{Thermalconductivity(Fourierequation)} f = -k \frac{\delta T}{\delta x} \frac{\delta T}{\delta y} \frac{\delta T}{\delta z} \quad (10)$$

$$\text{Radiationq} = \sigma\varepsilon\{(T - T_Z)^4 - (T_0 - T_Z)^4\} \quad (11)$$

Where ρ is the density, Q is the thermal energy, r is the radius, V is the volume, S is the surface area, σ is the Stefan-Boltzmann constant, ε is the emissivity, T_Z is absolute zero, T is the instantaneous temperature within the joining region, T_0 is the ambient temperature, x, y, z, are the coordinates, k is the conductivity matrix, f is the conduction heat flux, q is the radiation heat loss distributed and t is the time.
The geometry of the model adopted in the experiments is shown in Fig. 13.

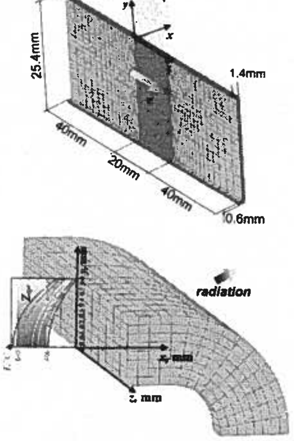
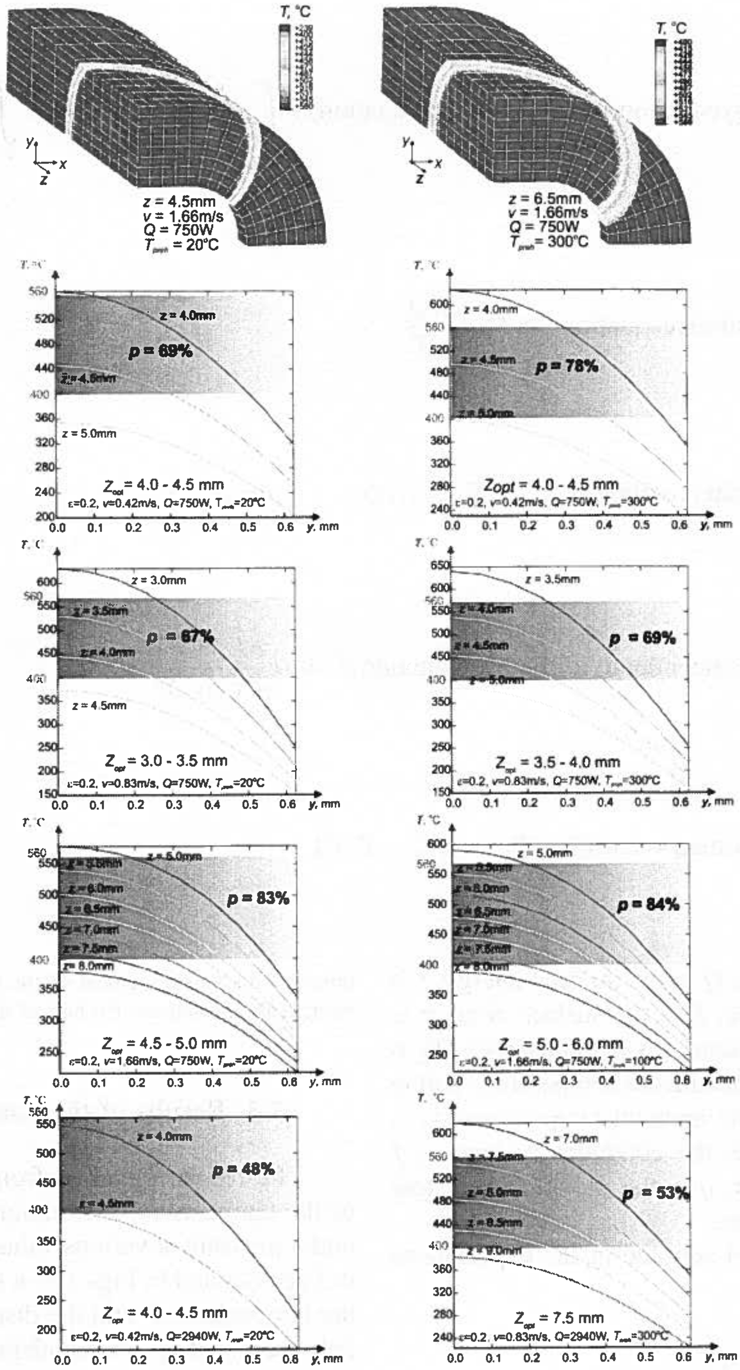


Fig. 13. Geometry of the numerical model of the analyzed rectangular tube: (a) the entire segment of the model taken into account in the numerical calculations, (b) half of the cross-section of the tube wall

2.5. Results of the numerical calculations

The results obtained from the numerical modeling of the temperature distribution within the joining region under pressure at various values of Z and T_{preh} are shown in Figs 14a and b. Figs 14c-n show the relations between the temperature T and the distance Z, the velocity v, the delivered heat Q. The modeling experiment was curried out various pre-heating temperature T_{preh} (Figs 14 c-n).


T, °C
z = 4.5mm
v = 1.66m/s
Q = 750W
T_preh = 20°C
z = 6.5mm
v = 1.66m/s
Q = 750W
T_preh = 300°C
p = 69%
Z_opt = 4.0 - 4.5 mm
ε=0.2, v=0.42m/s, Q=750W, T_preh=20°C
p = 78%
Zopt = 4.0 - 4.5 mm
ε=0.2, v=0.42m/s, Q=750W, T_preh=300°C
p = 67%
Z_opt = 3.0 - 3.5 mm
ε=0.2, v=0.83m/s, Q=750W, T_preh=20°C
p = 69%
Z_opt = 3.5 - 4.0 mm
ε=0.2, v=0.83m/s, Q=750W, T_preh=300°C
p = 83%
Z_opt = 4.5 - 5.0 mm
ε=0.2, v=1.66m/s, Q=750W, T_preh=20°C
p = 84%
Z_opt = 5.0 - 6.0 mm
ε=0.2, v=1.66m/s, Q=750W, T_preh=100°C
p = 48%
Z_opt = 4.0 - 4.5 mm
ε=0.2, v=0.42m/s, Q=2940W, T_preh=20°C
p = 53%
Z_opt = 7.5 mm
ε=0.2, v=0.83m/s, Q=2940W, T_preh=300°C
y, mm

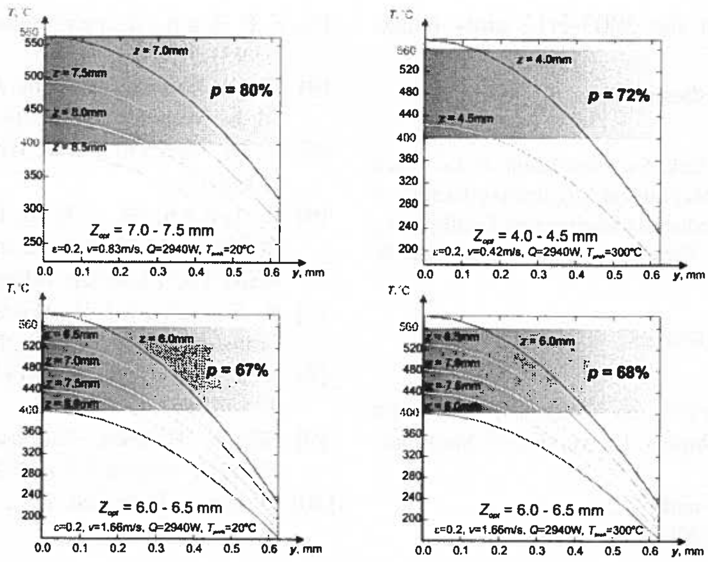


Fig. 14. Results of the numerical analysis: isotherms distributed on the tube wall thickness within the joining region; $\varepsilon = 0,2$ (emissivity assumed for the 4043-0 alloy according to [2]), v – linear traveling speed of the tube [m/s], Q – delivered heat, T_{preh} – pre-heating temperature, g – tube wall thickness 0,6mm, Z_{opt} – distance between the heat source and the pressing roll axis, p – joint quality parameter

The quality criterion of the joint was taken to be the parameter p (0-100%) which represented the portion (in percents) of the initial tube wall thickness that has been joined at a temperature between 673 and 833K (400-560°C). The higher the value of p, the greater the tube cross-sectional surface area heated to a temperature within the optimum temperature range.

Out of the results obtained from many modeling cycles, the results presented here seem to be most representative.

Certain results (especially those shown in Figs 14 i, j) suggest that the velocity v and the pre-heating temperature do not affect essentially the parameter p. Figs 14i-n, on the other hand indicate that, even when the amount of heat Q introduced into the system is high (2940W) and the material is pre-heated to 573K (300°C), the process parameters adopted in this series of experiments cannot ensure that the parameter p will exceed 80%. The distance Z ranged from 3,0mm to 7,5mm.

The situation becomes more advantageous if Q = 750W (Figs 14g, h) and the travel speed of the tube is $v = 1,66$m/s. The result is here better: $p = 84\%$. It is interesting that, at such a high value of v (1,66m/s), preheating of the tube has no greater significance: at T_{preh} = 373K (100°C) increases p by only 1%. If the preheating operation is omitted, the parameter p decreases to 83%.

3. Conclusions

It is difficult to formulate a precise definition of the proposed joining process. Since the process is a combination of two different joining methods conventional fusion welding and solid-state diffusion bonding, it would be justified to name it a hybrid technique of joining in the solid state.

The results obtained in the present modeling experiments show that it is possible to produce a good joint along almost the entire cross-section of the tube wall. Therefore, the aim of the present study, namely to find an alternative (in terms of efficiency) but less expensive method of joining parts made of the aluminum alloy, seems to have the chance to be achieved.

As follows from our experiments, the optimum set of parameters is: $v = 1,66$m/s, Q = 750W, T_{preh} = 293K (20°C), Z_{opt} = 4,5 – 5mm. In order to achieve a good reproducibility of the joints, special care should be taken that the distance Z and the velocity v are maintained precisely constant. The amount of introduced heat Q is not so critical. The numerical calculations show that the distance of the solid-state joining zone from the heat source, Z_{opt}, is twice as small as that estimated by the preliminary analysis based on simplified empirical results (see Section 2.3).

The joints produced using a plasma arc as the heat source contained imperfections that could be due to the hydrogen or carbon originated from organic impurities left after the plastic treatment of the tubes, or due to certain irregularities of the shape of the joining zone that resulted from instabilities in guiding the tubes by the pressing rolls. It seems, therefore, important to ensure the stability of the parameters of the plasma arc and of the traveling movement of the tubes, and only then to try to optimize the other parameters such as v and Z.

Another disadvantageous effect is cracking of the joint which may occur because of the laminar structure of the tube wall built of a 4943-0 alloy (4,5-6%Si) layer formed on the core made of the 3003-H12 alloy (max. 0,6%Si).

Acknowledgements

This work was supported by Dekaban Foundation. It was based on fruitful collaboration between Mechanical Engineering Faculty of the University of Michigan and Production Engineering Faculty o the Warsaw University of Technology. The author would like to thank A. Szwed for support in modeling).

REFERENCES

[1] J. Bunker, K. Lappo, N. Sheib, M. Van Belle, ME450 Group Report, University of Michigan, USA (2001).

[2] Material Property Data – web site: http//www.matweb.com. (2000).

[3] J. F. Lancaster, Metallurgy of Welding, 5th edition (1993).

[4] W. Włosiński, The Joining of advanced materials, ed. by Warsaw University of Technology (1999).

[5] C. M. Adams Jr., Welding Journal **37(5)**, 210-215, (1958).

[6] L. Chon, M. Chin, Heat Flow in Fusion Welding, Welding, ASM Hand Book, Brazing, and Soldering, 6, ASM The Materials Information Society, (1993).

[7] R. Siegiel, J. R. Howell, Thermal Radiation Heat Transfer, 2nd ed., Hemisphere Publishing Co (1980).

[8] R. L. Apps, D. R. Milner, Welding Journal **2(10)**, 475 (1955).

[9] Hibbit, Karlson, Sorensen, Abaqus/Standard Theory Manual, version 5.8 (1998).

[10] Wolfram Research Inc., Mathematica 4.0 – software (2000).

Received: 8 March 2008.