DOI: http://dx.doi.org/10.15407/tpwj2018.04.04

# DETERMINATION OF PARAMETERS OF FRICTION STIR WELDING MODE OF ALUMINUM-BASED ALLOY

**I.O. VAKULENKO** and **S.O. PLITCHENKO**
Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan
2 Lazaryan Str., 49010, Dnipro, Ukraine. E-mail: plit4enko@ukr.net

A procedure is proposed for determination of parameters of process of plates joining using friction stir welding technology by the example aluminum alloy. A nature of metal heating was determined in investigation of working tool rotation at different relationships of frequencies and normal pressing to joined edges. A minimum value of temperature interval in realizing of friction stir welding technology was determined from the analysis of nature of increase of heating temperature of edges being joined. Based on the analysis of received experimental data a concept of determination of main parameters of welding process was proposed. 17 Ref., 9 Figures.

***Keywords:*** *friction stir welding, heat energy, working tool; welding mode, aluminum-based alloys, optimum temperature*

Friction stir welding (FSW) relates to diffusion technologies characterized by absence of heating to metal melting temperatures (Figure 1).

The main source of heat in such a technology is a friction forces appearing between the metal surfaces being welded and working part of special tool [2–4].

With such a technology the intensity of necessary energy is determined by a complex effect of rotation frequency of the tool around its axis, pressing force and speed of its movement along the edges being joined under conditions of optimum geometry dimensions and shape of working tool [5].

At the same time high sensitivity of FSW process to insignificant changes of technological characteristics considerably complicates maintenance of the optimum welding conditions, especially when welding circuit differs from straight line. Indeed, under conditions of constant pressing force a relationship between rotation frequency and movement speed of working tool along the edges being joined allows control of the process of metal heating in a weld zone without difficulties. In contrast to this, it is more difficult to keep a stationary mode of welding only in varying pressing force when recommended temperature corresponds to narrow interval 0.8 – 0.95 from melting temperature of metallic material [5, 6].

Taking into account that the working tool determines the process of generation and distribution of heat energy in the welding zone, dimensions of its constituents and shape (Figure 2) significantly effect the welded joint quality.

Every part of the tool ensures performance of specific functions in transformation of mechanical energy into heat one by friction. Thus, shoulder provides approximately 80–90 % of necessary energy for edge heating [7], the rest is generated by pin. In such a way, the shoulder provides the main contribution in FSW under condition of necessary level of metal heating from mechanical contact.

The detailed analysis of structural transformations in the metal after FSW indicates that only specific shape of working tool guarantees the necessary distribution of heating temperature along intersection of contact surfaces [3, 8].

Depending on technological problems a special relief [9] can be made on the working surface of the

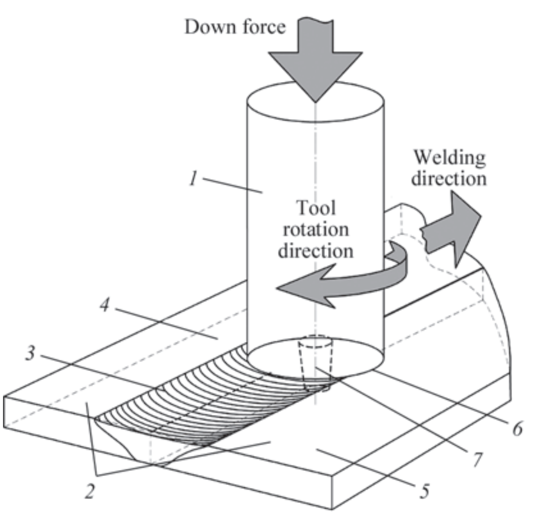


**Figure 1.** Process of welding of two plates [1]: *1* — tool; *2* — plates; *3* — weld; *4* — advancing side; *5* — retreating side; *6* — shoulder; *7* — pin

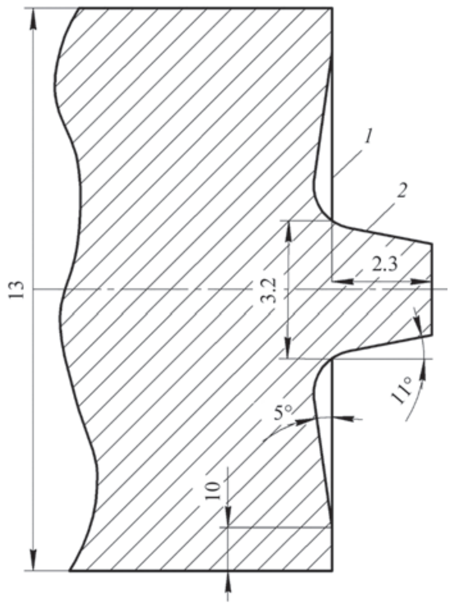


**Figure 2.** Schematic presentation of FSW working tool: *1* — shoulder; *2* — pin

tool, for example, for breaking oxide films or increase the level of metal stirring in edges being joined. Based on the results of investigations of works [2, 4, 10] performance of grooves enables getting increased level of complex of properties in welded joint metal.

A pin of the working tool in comparison with the shoulder has somewhat other designation. Its operation provides redistribution of heat energy sufficient for maintaining determined conditions of development of diffusion processes of metal mass transfer along the thickness of edges being joined during tool active operation.

The shape of working tool pin and its diameter have qualitative dependence on the series of factors, namely angle of its inclination in welding , thickness of the base metal, chemical composition etc. [7]. Making the grooves on pin surface in form of threads helps to control a flow of plasticized metal guiding it for compaction of some areas of the weld. Such an effect reduces the possibility of lack of penetration of weld root [8].

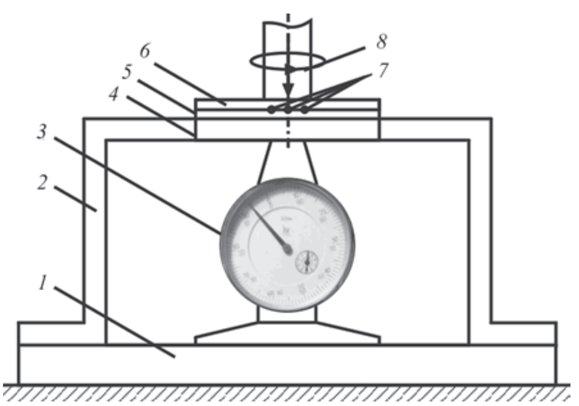


**Figure 3.** Scheme of bench for investigations: *1* — base plate of machine; *2* — bench framework; *3* — dynamometer; *4* — motion plate; *5* — heat insulator; *6* — sample being welded; *7* — thermocouples; *8* — working tool

In comparison with the technologies of partial or complete melting an application of FSW allows considerably reducing the level of metal overheating in a weld heat-affected zone. The perspective directions of application of such technology are joining of the elements of dissimilar materials which form heterogeneous melts or chemically unstable multiphase mixtures in solidification. The joints received on traditional technologies, for example, in electric arc welding, can have unpredictable negative effect on welded joint quality.

The aim of work is improvement of the procedure for determination of radius of working tool shoulder in FSW.

**Material and experiment procedure**. FSW was carried out on specially designed equipment that together with selected parameters of working tool [10–12] provided welded joint formation.

The FSW process (Figure 1) was performed on the following scheme, i.e. working tool *1*, with specific frequency of rotation around own axis, was located under 1–3° angle relatively to a plane of edges being joined. Constant normal force of the tool was necessary for deepening the shoulder at up to 10 % depth of edge thickness. Appearance of friction force on the contact surfaces of shoulder *5*, pin *6* and elements being joined *3* and *4* provide necessary level of base metal heating. Action of the pin results in uniform distribution of heat along edges thickness. The metal starts stirring after reaching the necessary level of heating.

A working tool material was high-speed steel R9, which provides maintenance of shape and size of the tool at increased heating temperatures when realizing FSW technology of the most aluminum-based alloys [5]. Shape and size of the working tool (Figure 2) was determined based on analysis of known experimental data [1, 3–5].

The investigations of FSW technology was carried out on the plates of 1.85 mm thickness from aluminum alloy AMg3 with content of chemical elements within the limits of grade composition.

Change of temperature in a welding zone and level of tool pressing was performed with the help of specially developed research bench (Figure 3) which was located on a base plate *1* of milling machine. The bench consisted of framework elements *2*, motion metallic plates *4* and heat insulator *5* made of mica. The pressing force of working tool to the base metal during welding was measured with the help of dynamometer of DS0.1 type with detecting head.

The temperature of heating of edges being joined T was determined by deepening of thermocouples of chromel-alumel type in the metal at different distance from weld axis. The speed of rotation of the working tool ω was varied from 800 to 1600 $min^{-1}$ at force of plates pressing to the surface not more than 1.45 kN. The speed of tool movement along the weld $v_w$ was constant and made 50 mm/min.

**Received results and discussion**. The level of metal heating was regulated in the process of investigation at different relationships of frequency of working tool rotation and its normal pressing to the edges being joined.

Figure 4 shows the results of effect of FSW process technological parameters on metal heating temperature in zone of action of the working tool shoulder.

The optimum temperature of heating of edge metal under conditions of rapid increase of ductile properties was determined from the analysis of $P = f(T)$ relationship nature. Independent on the tool rotation speed and force of its pressing the values of the minimum temperature lied in relatively low interval 70–85 °C. An average value of temperature 76 °C that corresponded to alloy plasticization moment was taken considering possible uncontrolled deviations at maintenance of stable conditions of welding process and in order to facilitate heat balance analysis.

A comparative analysis with the absolute values of temperature of start of resolidification development $T_r$ for different alloys on $T_r = 0.45T_m$ dependence, where $T_m$ is the metal melting temperature indicating sufficiently qualitative match between them.

The detailed analysis of curve shape $P = f(T)$ (Figure 4) taking into account staging of processes of structural transformations under conditions of hot reduction [13] indicates that the processes of internal rebuilding of alloy from the moment of formation of horizontal area to rapid decrease of pressing force are caused by development of dynamic processes of cell formation and resolidification at determined relationship.

Thus, the moment of formation of horizontal area can be accepted as the minimum value of temperature interval of FSW process and rapid decrease of $T$ is the maximum allowable value.

Shape of curves and the points of qualitative substitutions of $P = f(T)$ relationship indicate the dependence of conditions of achievement of metal superplastic state on FSW parameters. Really, if temperature of plasticization start remains virtually independent on ω and $P$ relationship than achievement of superplastic state (area of pressing force fall) to the larger extent is determined by ω value.

Evaluation of heat energy $Q$ necessary for FSW realizing was carried out in order to determine the parameter which has the largest effect on alloy ductility for different relationships of rotation speed and pressing force of the working tool. Taking into account that achievement of metal stirring conditions is heat activated process a well-known equation was used [14] for evaluation of $Q$:

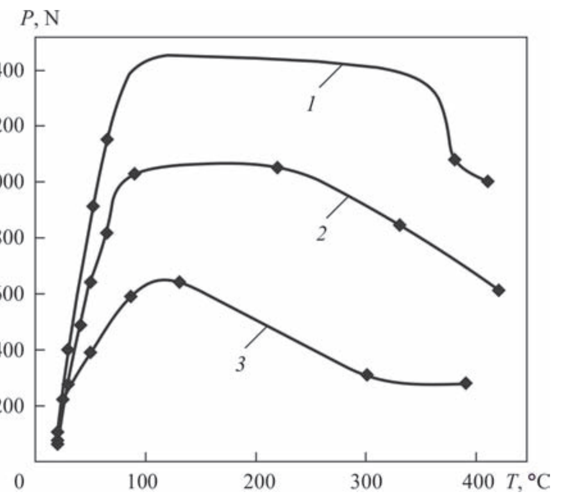


**Figure 4.** Experimental curves of effect of rotation speed ω and pressing force $P$ of working tool ($v_w$ = const) on heating temperature of alloy edges under shoulder: *1* — ω = 800; *2* — 1250; *3* — 1600 rpm

$$\dot{\varepsilon} = A\exp\left(-\frac{Q}{RT}\right)P^m, \tag{1}$$

where $\dot{\varepsilon}$ is the deformation rate; $A$ is the coefficient of proportionality; $R$ is the absolute gas constant; $T$ is the temperature (K); $P$ is the force characteristic; $m$ is the level index.

Under experiment conditions, relationship (1) was transformed to the form:

$$Q = RT(m\ln P - \ln\omega), \tag{2}$$

where ω is the rotation frequency; $P$ is the working tool pressing frequency.

The basic of $Q$ calculation made the experimental data (Figure 4) of different welding modes.

For edge thickness 1.85 mm, inserting the experimental values for steady mode in relationship (2): ω = 13.3 $s^{-1}$ (800 $min^{-1}$), $P$ = 1 kN; ω = 20.8 $s^{-1}$ (1250 $min^{-1}$), $P$ = 0.59 kN and ω = 26.7 $s^{-1}$ (1600 $min^{-1}$), $P$ = 0.275 kN for temperatures in zone of welding $0.7T_m$, the corresponding $Q$ values were received. Figure 5 shows the nature of $Q$ dependence on ω.

Provided results indicate that increased rotation frequency under conditions of constant welding speed ensures heating to necessary temperature in the welding zone at lower level of energy.

Thus, reduction of necessary energy can be reached by decrease of normal pressing force of the working tool to billets at rise of ω in process of welding that is proved by curve *3* on Figure 4.

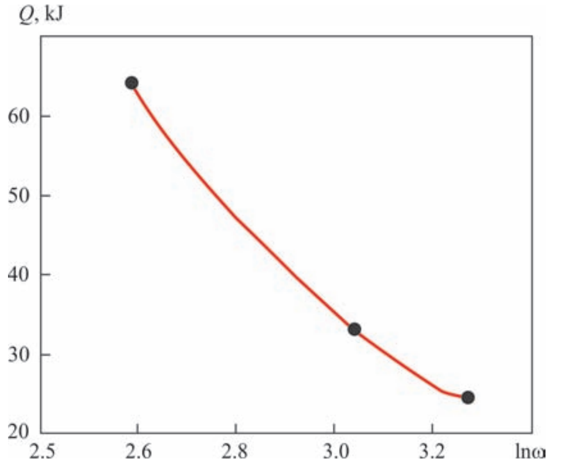


**Figure 5.** Dependence of value of energy $Q$ for steady welding process (at $0.7T_m$) on working tool rotation frequency lnω and pressing force at $v_w$ = const

Together with this under conditions of minimum force $P$ (0.275 kN) another nature of change was determined, i.e. calculated using (2) amount of energy on frequency of working tool rotation (Figure 6).

Joined analysis of calculated values $Q$ (Figures 5, 6) indicates the need to determine the optimum energy for friction stir welding and possible dependence on geometry of the working tool. There was an attempt to evaluate the optimum diameter of the working tool shoulder for different thicknesses of edges being joined taking into account a contribution of the shoulder into energy balance in FSW. For this purpose a relationship of dependence of FSW process heat balance on main technological parameters [15] was used:

$$N = \frac{2}{3}\pi\mu p\omega R_{\text{tool}}^3, \tag{3}$$

where $N$ is the energy characteristic; μ is the friction coefficient; $p$ is the specific normal pressure of the tool; ω is the angle rotation speed; $R_{\text{tool}}$ is the tool shoulder radius.

From relationship (3), $R_{\text{tool}}$ equals

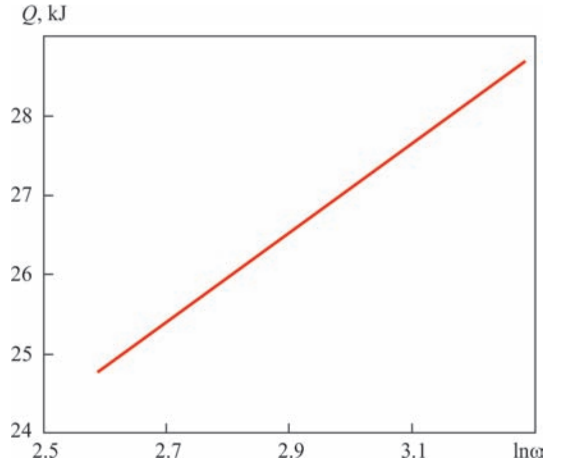


**Figure 6.** Dependence of amount of energy $Q$ for steady welding process on working tool rotation frequency (lnω) at $P$ = 0.275 kN, $v_w$ = const by relationship (2)

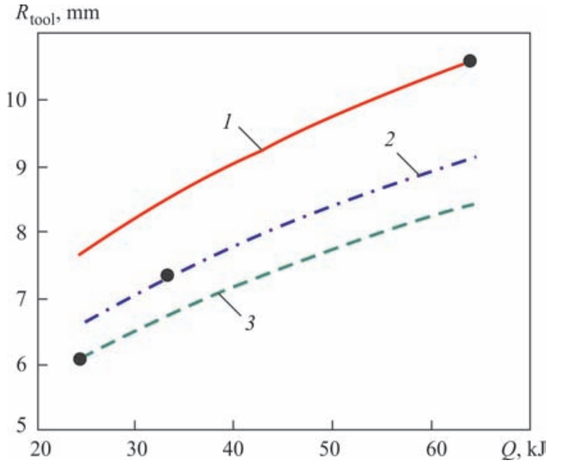


**Figure 7.** Diagram of selection of working tool shoulder radius $R_{\text{tool}}$ for steady welding mode at $P$ = 0.275 kN, $v_w$ = const and δ = 1.85 mm: *1* — ω = 800; *2* — 1250; *3* — 1600 rpm; • — $Q$ value from analysis Figure 5

$$R_{\text{tool}} = \sqrt[3]{\frac{3N}{2\pi\mu p\omega}}. \tag{4}$$

The results of $R_{\text{tool}}$ calculation by (4) using hypothetical values of $Q$ for investigated intervals of P and ω change are given in Figure 7.

Evaluated values $Q$ from experiment [16] were used instead of $N$ in order to check fulfillment of dependence (4). Received results on $R_{\text{tool}}$ for the experiment conditions in FSW for δ = 1.85 mm indicate sufficiently qualitative match with that calculated by (4).

The analysis of the results of experimental investigations and carried calculations prove existing dependence of value of heat energy in the welding zone, first of all, on radius of working tool shoulder, namely reduction of $R_{\text{tool}}$ results in $Q$ decrease.

In process of welding position of the tool at 1–3° angle relatively to normal line of the billet provides the necessary conditions for metal compaction. Expected nonuniformity of temperature distribution along the area of contact spot (shoulder) takes place only at initial stages before coming to the optimum welding conditions. After that steady conditions of the process of heat energy emission are reached.

Designing of the working tool requires taking into account that diameter of the shoulder determines level of mechanical loads on the equipment in whole, as well as, width of heating zone. Under conditions of higher speeds of working tool rotation the excessive increase of $R_{\text{tool}}$ can result in overheating of welded joint that will have negative effect on its mechanical properties. Received qualitative dependencies are proved by the experiment, i.e. the optimum welding conditions are rather achieved at rise of ω and decrease of $P$.

At the same time it is necessary to expect specific effect on technological characteristic when reaching the optimum welding mode from the side of chemical

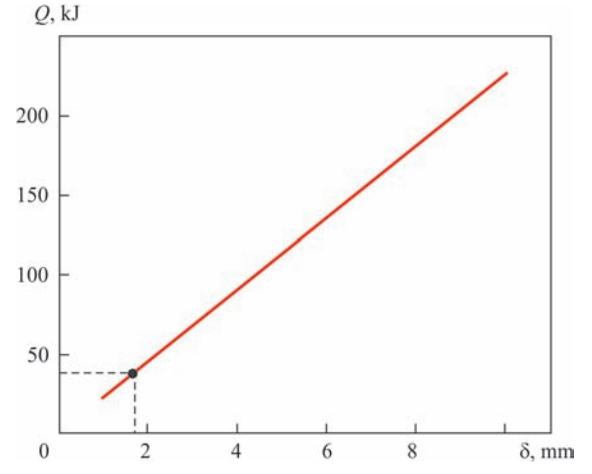


**Figure 8.** Dependence of necessary amount of energy $Q$ by (5) for steady welding process on metal thickness δ

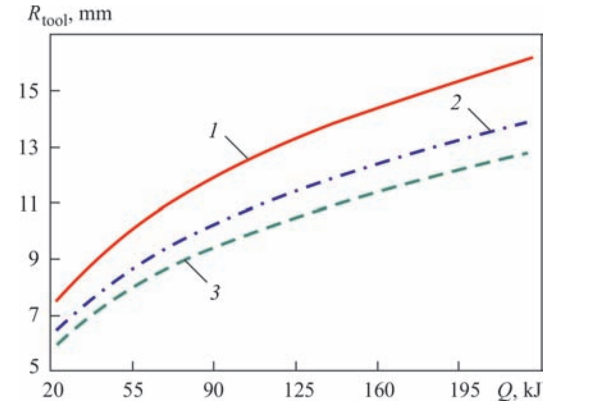


**Figure 9.** Diagram for determination of recommended radius of working tool shoulder $R_{tool}$ for reaching steady welding process at $P = 0.275$ kN, $v_w$ = const: *1* — ω = 800; *2* — 1250; *3* — 1600 rev/min

and phase composition of alloy. The total contribution can be evaluated through correlative relationships of heat physical properties.

Following similarity criterion ψ it is possible to determine the necessary energy for welding depending on plate thickness δ [17]:

$$\psi = \frac{N}{\lambda T \delta}, \tag{5}$$

where $N$ is the characteristic similar to $Q$ from (3); λ is the heat conductivity; δ is the thickness of metal edges; $T$ is the temperature in welding zone, K.

Based of relationship (5) for specific alloy under conditions of constant λ and $T$ (the optimum temperature of edge heating in FSW) ψ value varies in a very small range of values that is proved by the data [17] and experimentally in the work. Taking into account that thickness of metal being welded can be changed in a wide range, calculations of $R_{tool}$ are limited by thicknesses from 1 to 10 mm that is the most widespread in industry.

After inserting in (5) the constant characteristics λ, $T$ and ψ (was taken as constant value) the relationship between δ and $Q$ was received for steady FSW mode (Figure 8). Taking into account that $Q$ of the same level can be reached by different combination of ω and $P$, the calculation of welding energy by (5) in reality provides an average value for a range of changes of ω and $P$ that has determined prove. Thus, for δ = = 1.85 mm thickness an obtained value of energy by relationship (5) and average $Q$ value following three modes (40 kJ) have sufficiently qualitative match.

Thus, provided dependence (Figure 8) allows determining the optimum FSW conditions for different thickness plates. For example, the necessary value of heat energy for δ = 3 mm thickness should make the value around 70 kJ. Then, using energy value for specific equipment with determined power the optimum frequency of working tool rotation and corresponding radius of shoulder are evaluated.

Taking into account that plotted relationship $R_{tool}$ = = $f(Q)$ (Figure 7) is only referred to edge thickness 1.85, Figure 9 provides more generalized example, when 1 < δ < 10 mm.

At the same time, plotted diagram (Figure 9) in fact refers to the conditions of constant pressing force (0.275 kN), however, the optimum level of $Q$ for welding (FSW) is determined by combination of ω and $P$.

Verification of dependence fulfillment (Figure 9) was carried out experimentally. Thus, under conditions of constant pressing force (0.275 kN) for welding of 3 mm thickness edges at ω = 1250 rpm the tool radius shall be in 9–10 mm range and for 1600 rpm frequency it is approximately 8–9 mm. Under conditions when proved necessity of searching the optimum welding mode is based on change of working tool pressing force, $R_{tool}$ calculation is carried out using other diagram for specific $P$ value.

Thus, provided evaluations make it possible to improve the process of searching the optimum welding parameters by friction stir welding.

## Conclusions

1. The main conditions for reaching the effect of constant softening of metallic materials in FSW were determined by the example of aluminum-based alloy.

2. The minimum value of temperature interval of metal softening in FSW was determined.

3. A procedure of shoulder radius selection depending on the relationship of rotation speed and working tool pressing force in FSW was developed for different thicknesses of edges being joined.


1. Thomas, W.M., Nicholas, E.D., Needham, J.S. et al. (1991) *Friction stir butt welding*. Int. Pat. Appl. PCT/GB 92/02203; GB Pat. Appl. 9125978.8. Publ. 1991.

2. Schneider, J.A. (2007) Temperature distribution and resulting metal flow: *Friction stir welding and processing*, 37–49.
3. Makarov, E.L., Korolyov, S.A., Shtrickman, M.M., Kashchuk, N.M. (2010) Modeling of thermal processes in friction welding. *Svarka i Diagnostika,* **3**, 21–25 [in Russian].
4. Mishara, R.S., Mahoney, M.W. (2007) *Friction stir welding and processing*. Ohio, ASM International.
5. Poklyatsky, A.G., Ishchenko, A.Ya., Podielnikov, S.V. (2008) Influence of friction stir welding process parameters on weld formation in welded joints of aluminium alloys 1.8–2.5 mm thick**.** *The Paton Welding J*.**, 10,** 22–25.
6. Song, M., Kovacevic, R. (2003) Numerical and experimental study of the heat transfer process in friction stir welding. In: *Proc. Ins. Mech. Eng., B.J. Eng. Manuf*., IMECHE, **217**, 73–85.
7. Vakulenko, I.O., Mityaev, O.A., Plitchenko, S.O. (2014) On structure transformations in friction stir welding of aluminium alloy. In: *New materials and technologies in metallurgy and mechanical engineering*. Zaporizhzhya, 1, 8–10 [in Ukrainian].
8. Schneider, J.A., Nunes, A.C. (2004) Characterization of plastic flow and resulting microtextures in a friction stir weld. *Metall. Mater. Trans*. **B**, **35**, 777–783.
9. Colligan, K. (2003) *Tapered friction stir welding tool*. Int. Pat. Appl. 10/140,797; US Pat. 6,669,075 B2. Publ. 30.12.2003.
10. Vakulenko, I.O., Plitchenko, S.O. Nadezhdin, Yu.L. (2012) Application of friction stir welding technology of aluminium alloy. *Visnyk Dniprop. Nats. Zalizn. Transport. Univers. V. Lazaryana*, **41**, 230–233 [in Ukrainian].
11. Vakulenko, I.O., Plitchenko, S.O. Nadezhdin, Yu.L. (2012) *Method of friction stir welding of aluminium-based alloys***.** Ukraine Pat. 75698, Int. Cl. B23K 1/00. Fill. 29.05.12; Publ. 10.12.12 [in Ukrainian].
12. Reynolds, A.P., Schneider, A.P. (2007) Microstructure development in aluminum alloy friction stir welds. In: *Friction stir welding and processing*, 51–70.
13. Vakulenko, I.A., Bolshakov, V.I. (2008) *Morphology of structure and strain hardening of steel*: Monography. Dnepropetrovsk, DNU [in Russian].
14. Hayes, R.W., Hayes, W.C. (1982) On the mechanism of delayed discontinuous plastic flow in an age-hardened nickel alloy. *Acta Metallurgica*, **30**, 1295–1301.
15. Vill, V.I. (1970) *Friction welding of metals*. Leningrad, Mashinostroenie [in Russian].
16. Vakulenko, I.O., Plitchenko, S.O. (2017) Determination activation energy of friction stir welding. In: *Proc. of 9th Intern. Conf. of Young Scientists on Welding and Related Technologies (23–26 May 2017, Kyiv, Ukraine)*. Kyiv, 54–58.
17. Erokhin, A.A. (1973) *Fundamentals of fusion welding. Physical-chemical principles*. Moscow, Mashinostroenie [in Russian].


Received 23.02.2018