DETERMINATION ACTIVATION ENERGY OF FRICTION STIR WELDING

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Abstract. According to the technology of friction stir welding (FSW) heating of the edges is equal to 0.85–0.9 from the melting temperature of metal (T). Increase in temperature is accompanied by increased degree of the metal stirring, which leads to ambiguous influence on the metal density and concentration of cavities at different distances from the welding joint. At the same time, the temperature gradient across the section of joint leads to a different speed of recrystallization processes development and forming of structural heterogeneity in metal edges. Thus, the relevant question is to determine the optimal scheme of metal edges heating during the implementation of FSW technology. Material for the study was alloy AMg5. For different ratio of rotation speed and pressure on operating tool there were obtained the conditions of superplastic state of alloy at the temperatures of heating at the level of 0.45–0.5 from T, which corresponds to the beginning of dynamic recrystallization development during FSW. At the same time, it was evaluated the energy of activation (EA) of FSW process. Using the analysis of the obtained results it was determined the fact that when reaching the same temperature of alloy heating the EA value of FSW process decreases with increasing the rotation frequency of the operating tool and decreasing the degree of its pressing to the edges of welding joint. On the basis of the above mentioned the development of FSW technology should be directed toward the use of high speed rotations of the operating tool and low levels of its pressing to the alloy edges.

Key words: activation energy, rotation tool, pressing, joint edges, aluminum alloy.

1. INTRODUCTION

Friction stir welding (FSW) belongs to thermal technology and can be used to connect both metal and non-metal materials. Welded edges warming is achieved by transforming mechanical energy by friction, from the interaction the edges of the surface of the tool into heat. Suffice complex form of working tools is caused by necessity of specific temperature heating distribution on the connecting edges when using the specified welding technology. Compared to welding technologies, based on partial melting of the connecting edges, the use of friction stir welding helps reduce degree of overheating the metal heat affected zone. On this basis it should be considered perspective directions of use of the welding technology for metallic materials with thermally unstable structures, structures with very small grain size, etc.

A special feature of the process of FSW is no change in the physical state of the metal material. Analysis of the results known experimental studies [1, 4, 6, 10] shows the dependence of the quality of the weld seam to the specified welding technology not only on the growth of the plastic properties of metal, but on achieving a certain degree of stiring zone of connecting edges. So, one of the explanations for the positive impact of the increase in temperature heating edges based on growing degree of stiring, that in turn improves metal density by reducing the number of cavities in the joint zone. Based on this, the formation of welded joints in large degree shall be determined by features of the development diffusion mass transfer processes, and increase the degree of heating the metal is quite reasonable solution [8–10]. The analysis much research the internal structure of metallic materials after forming the welded seam by FSW technology indicates quality coincidence with the structural condition of the metal after hot plastic deformation.

According to the results of structural changes [7] and direct measurement of the temperature in the welding zone [8], in most cases, to get a quality joining offered heating the metal edges to prove the level of 0.8–0.9 melting temperature. At the same time, quite high sensitivity of metal materials to overheat connecting edges of accelerate the processes of building recrystallization, limiting uncontrolled heating of the weld seam area. Definition of balance between the two influences in character of the opposite direction, at the quality of the weld seam is actual technological issue.

2. METHODOLOGY

The material for the research was alloy based on aluminum (brand AMg5) with chemical composition: 4,8% Mg, 0,5% Mn, 0,36% Fe, the rest Al. The plates 2.5 mm thick were exposed to butt welding, FSW in a specially designed facility that allows to change the technological parameters in a wide range of values (Fig. 1). The form of working tool shown in Figure 2.

As material for the working tool was used speed steel R9 brand that ensures the stability of the geometric dimensions while warming up to certain temperatures. For different ratios of frequency of rotation of the tool, the normal pressing and moving it along the connecting edges determine the degree of heating metal and forming of weld quality.

The temperature of the warming connection edges defined by thermocouples (chromel-alumel) immersed in metal, which were placed at different distances from the joint weld. Rotation speed of (v) working tool changed in the range from 800 to 1600 rpm, while pressing his effort to the plates in the welding zone (P) from 580 to 1370 H and the rate of movement along the seam 50 mm/min.

Assessment of activation energy of FSW process was carried out according to the method [11], which was used for thermally activated processes.

3. FINDINGS

During welding ZTP, depending on technological parameters formed surface of weld different degree of quality (Fig. 3).

Provided to constant pressure forces on the connecting edge and speed of working tool moving along the joint weld, increasing the frequency of rotation is accompanied by an expected decrease mechanical damage of the metal surface in place of shoulder tool (Fig. 3*b*) and corresponding structural changes in the internal structure of the alloy (Fig. 4). This provision is explained by the different degrees of warming edges and bound with this level of plastic properties of the alloy, which leads to the formation of appropriate structural changes in the work area of the tool (Fig. 4*b*). To achieve the same degree of metal warming on

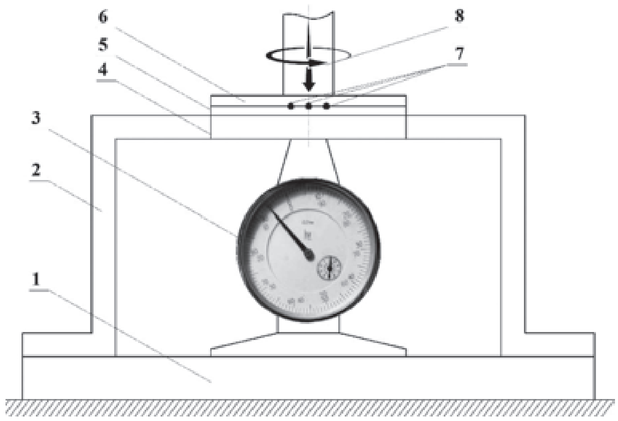

Fig. 1. Schematic representation of equipment for research: *1* — base plate; *2* — table; *3* — device for measuring the strength of the pressure; *4* — moving plate; *5* — thermal isolator; *6* — welding plates; *7* — thermocouples; *8* — work tool

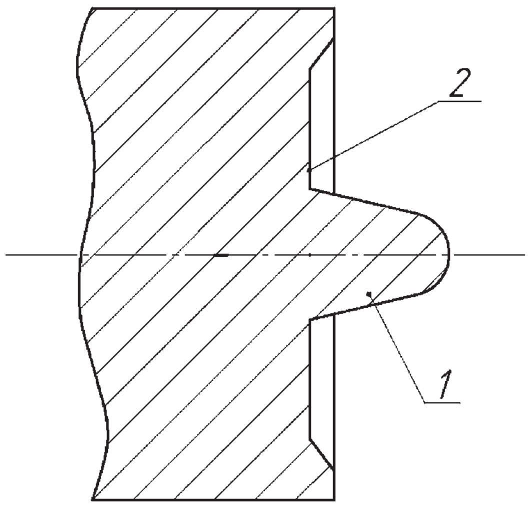

Fig. 2. Schematic view of the active part of the working tool [2]: *1* — pin; *2* — shoulder

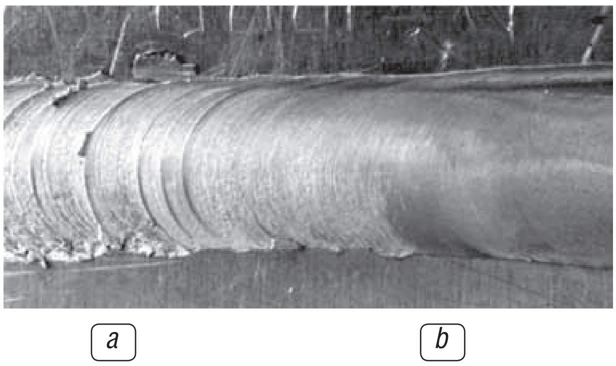

Fig. 3. The exterior surface of the weld seam, depending on the rotation speed of the tool: *a* — v=800 rpm; *b* — v=1600 rpm

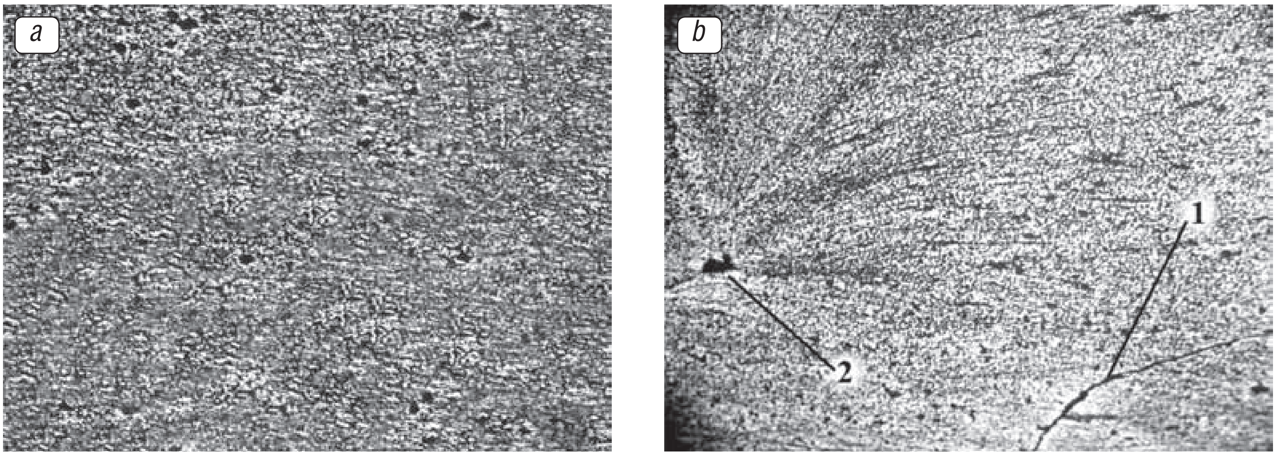

Fig. 4. The structure of the alloy AMg5 in original condition (*a*) and after the formation of the weld (*b*) (magnification ×50): *1* — boundary welded baths; *2* — bottom weld

tool contact area "edge — shoulder" possible by increasing force pressing and decreasing rotation speed. On the basis of defined ratios raises the question to optimize FSW technology process. Fig. 5 shows the research results of influence of technology parameters FSW on the temperature warming the metal in the area shoulder of the working tool. In appearance dependence can be separated into two categories, with qualitatively different character of temperature changes.

At first, independently of the ratio of rotation speed and instrument pressing strength to edges, moment of infraction directly proportional character of the temperature increase from *P* corresponds to the same value, approximately

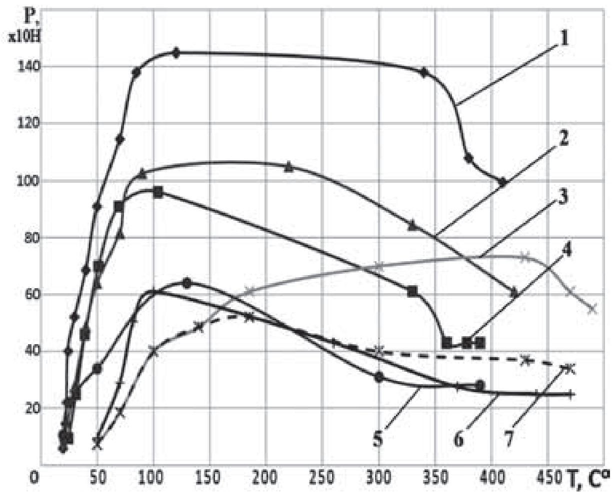

Fig. 5. The experimental curves influence of rotation speed (1, 4 — 800; 2, 3 — 1250; 5, 6 — 1600 rpm) and consistent increase of pressing strength (*P*) on the heating temperature of alloy edges under the shoulder of the working tool.

80–90°C. Further increase in the heating temperature of the metal was at the same pressing level (relatively low rotation speed) or steady decline *P* at high levels *v*. The changing character of the relation between technological parameters of FSW and heating temperature can be conditioned only by development of structural changes in the alloy during action tool. Indeed, given the character of the relationship between "temperature — pressing force" in large degree is similar to the achievement conditions of development processes of superplastic state during a hot plastic deformation of metallic materials [3]. Characteristic feature of achieving very high levels of metal plastic properties is performing a particular correlation between the rate of hot deformation and development of processes dynamic softening [2].

Considering the existence of substantial convergence signs of plasticizing alloy [3] and the nature of the change in temperature (Fig. 5), was an attempt to determine compliance between temperature curves fracture and features to internal restructuring of the studied alloy.

For metallic materials ratio between the temperatures development of the static recrystallization process (T_r) and melting (T_s) has the form [5]:

$$T_r \approx 0,4T_s\,. \quad (1)$$

Taking T_s as the temperature "solidus" from diagram state of the investigated alloy (873K), temperature rating by (1) determined that T_r should be approximately 349K (76°C). Thus, for the investigated alloy temperature of beginning of recrystallization development under static conditions will be equal to 76°C. Considering the existence of the incubation period, required to start the development process of static or dynamic recrystallization [3, 5] in the process of hot deformation (work of FSW tool) moment of achieving intensive softening of the alloy must be dislodged toward the higher temperatures. Entirely proved that the moment of fracture at the dependencies (Fig. 5) as compared with static conditions development of the recrystallization is dislodged toward higher temperatures to 80–90°C.

Thus, Friction Stir Welding can be performed at lower heating temperatures compared to those offered to use in most studies (0,8–0,9 T_s). This will allow to receive more homogeneous, finely divided grain structure in the alloy in heat affected zone after FSW.

Enough high sensitivity of metal materials to heating temperature at the connecting edges FSW in fact conditioned by the influence of two mutually dependent factors: the quality of mixing metal and level of plastic properties. For a low level of plastic properties mixing quality of metal in the welding zone will be insufficient, that will lead to the formation of a welded seam with a high concentration of defects of various shapes and sizes. On the other side, when overheated metal to a temperature above the optimum value, excessive plasticizing will also have negative consequences. Indeed, besides the excessive grain growth of the matrix alloy under these conditions will be the decrease frictional forces between the surface of working tool and workpiece. In consequence, the alloy to a lesser degree will capture by the surfaces of working tool that lead to lower extent of its mixing and connection quality edges after FSW.

To determine the characteristic that has compulsory influence on the quality of the weld seam formation, for different ratios of rotation speed and pressure of working tool, performed assessment of activation energy (Q) transition alloy in superplastic state. Given that achieving conditions of stirring metal is thermally activated process, to assess Q use the equation type [11]:

$$\dot{\varepsilon} = A \exp\left(-\frac{Q}{\mathrm{R}T}\right) P^m, \qquad (2)$$

where $\dot{\varepsilon}$ — the rate of deformation; A — coefficient; R — universal gas constant; T — temperature (°K); P — power characteristic; m — exponent.

To assess the value Q of the experimental curves (Fig. 5) were selected three curves (Fig. 6). Taking as a characteristic of deformation rate value v, and for P — pressure tool at the edges, after taking the logarithm of equation (2) obtain the value that allow to determine the characteristics for the evaluation of activation energy:

$$\ln v = \ln A - \frac{Q}{\mathrm{R}T} + m \ln P, \qquad (3)$$

Given that is A the value of the rate of deformation in conditions where $m \to 0$, to assess Q its influence can be disregarded [11]. In these circumstances, equation (3) takes the form:

$$\ln v = -\frac{Q}{\mathrm{R}T} + m \ln P, \qquad (4)$$

Given the achieving constant temperature of 85–90°C (Fig. 6), constructed the ratio between paired values $\ln v$ and $\ln P$, the result is shown in Figure 7. The value of the exponent m defined as the tangent of angle slope for individual sections of dependencies (Fig. 7):

$$m = \frac{\Delta \ln v}{\Delta \ln P}, \qquad (5)$$

After substituting in (4) experimental characteristics (v, P and calculated m) were identified value Q. The analysis of values Q shows that when the rotation speed of the tool is equal 800 rpm, and the value of pressure is equal 1370 H, to achieve the same degree of alloy heating is necessary to spend about twice as much energy as the conditions v=1600 rpm and P=580–590 H. One of the confirmation of specified conclusion is

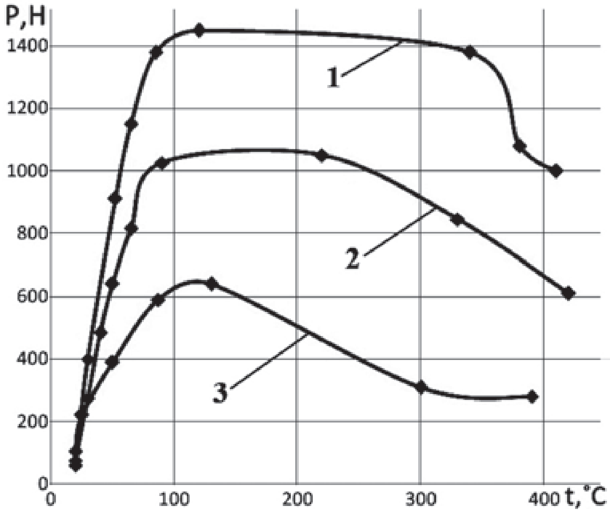

Fig. 6. Curves to calculate Q the alloy: *1* — v=800 rpm; *2* — v=1250 rpm; *3* — v=1600 rpm

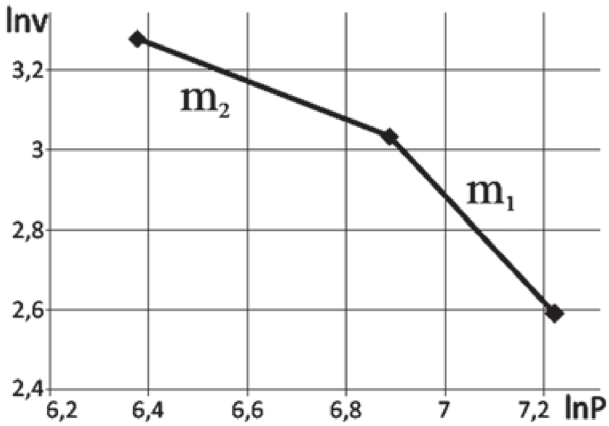

Fig. 7. The view of ratio $\ln v - \ln P$ for temperatures 85–90°C

temperature existence area of constant pressure level. Indeed, in conditions when the rotational speed is equal 800 rpm, area of constant pressure level exists up to temperature of 350°C and only then begins permanent alloy softening (see Fig. 6, curve 1).

Temperature range (ΔT) is about 250°C. Proportional increase v value ΔT reduced of 125°C for 1250 rpm to 50°C for 1600 rpm. Thus, in determining optimal process conditions friction stir welding should give priority to technological parameters directed at increasing the speed rotation of the working tool and lowering its pressure to the connecting edges.

4. SCIENTIFIC NOVELTY AND PRACTICAL SIGNIFICANCE

At a constant rotation speed of the working tool, a proportional increase in temperature of the alloy by increasing its level of pressure to the connecting edges, disrupted achievement the conditions of dynamic processes softening.

Evaluation of the activation energy development of the process friction stir welding allowed to define directions of choice technological parameters preferring increase the speed rotation of the working tool and reduce its pressure to the connecting edges.

5. CONCLUSIONS

1. On the basis of different ratios rotation speed of working tool and pressure to the connecting edges specified the conditions of achieving the effect of constant softening during friction stir welding.

2. To achieve the high quality weld seam during FSW need to realize the process at high revs of working tool and low pressure to the connecting edges.

REFERENCES

1. *Vakulenko I. O., Plitchenko S. O., Nadezhdin Y. L.* Use of Friction stir welding for aluminum alloy // Bulletin of Dnipropetrovsk National University of Railway Transport named. Acad. V. Lazaryan. Dnepr. — 2012. — Vol. 41. — P. 230–233.
2. *Vakulenko I. O., Mityaev O. A., Plitchenko S. O.* About structural changes during friction stir welding of aluminum alloy // New materials and technologies in metallurgy and machine building. Zaporozhye. — 2014. — Vol. 1. — P. 8–10.
3. *Vakulenko I.A., Bolshakov V.I.* Morfologiya struktury i deformatsionnoye uprochneniye stali // Structure morphology and strain hardening steel. — Dnepropetrovsk: Makovetskiy Publ., 2008. — 196 p.
4. *Vakulenko I.A., Plitchenko S.A*. Evaluation of the activation energy of the plastic flow during friction stir welding [Titan 2016: Vibrant in the Aviabaduvannia: Tez. IV міжнар. Sciences-practical. Conf. (3.11–4.11.2016)] Ministry of Science and Science of Ukraine, AT "Motor Sich", Zaporozhye national technical university. — Zaporozhye, 2016. — P. 96–98.
5. *Dzugutov M.Y*. Plastic deformation of high-alloy steels and alloys. — M: Metallurgy, 1977. — 480 p.
6. Pat. 5,460,317. USA, Friction welding [Текст] / W.M. Thomas, E.D. Nicholas, J.C. Needham at al.; assignee The Welding Institute Cambridge, United Kingdom; public date: 10.06.1993; public № WO93/10935.
7. *Gould J.E.* Heat Flow Model for friction stir welding of aluminum alloys / J.E. Gould, Z. Feng // Mater. Process. Manuf. Sci. — 1998. — Vol. 7. — P. 185–194.
8. *Reynolds A.P*. Microstructure development in aluminum alloy friction stir welds [Текст] / A.P. Shneider // Friction stir welding and processing. — 2007. — P. 51–70.
9. *Dawes C.J.* An introduction to friction stir welding and its development // Weld and Metal Fabr. — 1995. — № 1. — P. 13–16.
10. *Kallee S., Nicholas D.* Causing a stir in the future // Welding and Joining. — 1998. — № 2. — P. 18–21.
11. *Hayes R.W., Hayes W.C.* On the mechanism of delayed discontinuous plastic flow in an age-hardened nickel alloy // Acta Met. — 1982. — Vol. 30. — P. 1295–1301.