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Structural transformations at friction stir welding of aluminum alloy.

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Abstract. On example of aluminum alloy AMg6 the questions concerning development processes of structure formation during friction stir welding are considered. From analysis changes in technological parameters of welding process, a qualitatively different nature of the temperature change is determined when approaching conditions of the super plastic deformation. In accordance with determined heating temperatures, effect grain size of solid solution on hardness in micro volumes of the alloy after forming weld joint was analyzed. From analysis dependence of micro hardness on grain size, it is determined that as the temperature increases, contribution to achieving conditions of super plastic flow from the grain boundaries with large angles of disorientation increases, and effect from solid solution state are decreases.

Keywords: grain, size, hardness, friction stir welding, recrystallization

1. Introduction

The process of friction stir welding (FSW) is carried out without changing aggregate state of metallic material. In terms of energy used to heat connecting edges, the FSW refers to mechanical technology. The results of studies [1-3] determine dependence of quality of the weld on a number technological factors, the action of which aimed at achieving desired level plastic properties of metal for qualitative mixing in the area joined edges. Under such conditions, the technology of friction stir welding is determined primarily by development processes of diffusion mass transfer over the action of working tool. On this basis, increasing degree of heating metal according to numerous experimental data [4-6] is a well-founded solution, and quality of welded joint should be proportional to heating temperature. At the same time, according to [2,3], the role of development processes of structural transformations, which determine complex of properties and, first of all, characteristics of strength welded joint, is emphasized. Excessive rise metal temperature in tool zone is accompanied by a corresponding acceleration of structural transformation at dynamic and static conditions. The high sensitivity FSW technology to the temperature and velocity of plastic deformation often cause complications in the management of structure formation processes. As a consequence, in structure of the weld metal, difference in size and shape of the grains can reach large levels, which has a negative impact on the properties of the welded joint. The study conditions development of structural transformations at FSW with the involvement of various models, including achievement of super plastic state in metallic material, will be the key to improving the technology FSW.

2. State of question

The defined shape of working tool provides simultaneous heating and mixing metal edges in thickness and in the plane one surfaces of the weld. The shoulder of working tool helps to reduce temperature gradient in weld zone, and pin provides transition metal along entire thickness of the edges to super plastic state with appropriate mixing. Under conditions development of super plastic deformation of metallic material, the effective stress is proportional to grain size, which is subject to dependence:

$$\sigma = Ad^{a}, \tag{1}$$

where d is grain size, $a \approx 1$ [7], A is constant [8]. On this basis, the purpose of obtaining structure with smallest grain size is quite reasonable. The optimal size range is from one to several microns. The second factor - achieving high levels plastic properties and maintain the grain size unchanged during plastic deformation. Under conditions of appropriate correlation of temperature and velocity plastic deformation, the characteristic feature of the achievement of super plastic state is constant or reduction of stress during deformation. Given that for single-phase alloys, the main structural element is grain size and shape, maintaining a defined grain size distribution ratio is considered the key to achieving high levels of plasticity. This is due to need maintain the conditions of continuous distribution plastic flow in various micro volumes of metal. The analysis of deformation distribution shows dependence of its distribution on grain size. Thus, the smallest grains are deformed forcibly along boundaries with large angles of disorientation [9], which is ensured low level of active stress. While grains of relatively large size are deformed throughout the volume, there is a need for continuous increase in operating stresses. It is believed that such mechanism can be implemented for alloys with low homologous temperatures. Thus, for different groups grains (relatively large and small sizes) development of super plastic deformation can be expected under different mechanisms. At temperatures below optimum value, when the plastic properties of metal become insufficient to achieve desired level of mixing, traces from action of the working tool become rougher, with clear signs separation of the dispersed fragments. Under conditions when the overheating of metal to temperatures higher than optimum value is achieved, as shown in [10], the thermal impact zone and the seam region have strength properties of a much lower level compared to derivative state. The preservation of partial influence from development of deformation hardening processes during propagation of plastic flow can be a factor increasing the strength of metal in the weld area to level of the derivative state. When the temperature interval significantly exceeds conditions maintaining balance between the accumulation of crystalline structure defects during the FSW and their annihilation, for example, to the levels of 0.8-0.85 from melting point [3], the mechanism of structure formation in metal may be qualitatively different. According to [11], the super plastic deformation accompanied by rotation randomly oriented grains relative direction of acting stress, or alternation of slip in volumes of metal near grain boundaries, with their subsequent migration [12], like development of secondary recrystallization.

Purpose. Determination of mechanism influence grain size on micro hardness of aluminum alloy after friction stir welding.

3. Material and methodology

For the studies selected aluminum alloy *AMg6* contained *Mg* 6,5%, *Mn* 0.85%, *Fe* 0.13%, the rest of *Al*. Sheets with a thickness of 2.9 mm were welded, using the FSW technology on specially designed equipment [4,5]. Degree of heating metal was determined at different speed ratios (ν) of the work tool (800 - 1600 min^{-1}) and normal pressing (*P*) of 0.58 - 1.4 *kN*, at constant speed of movement along the connecting edges (40 mm/min). Temperature (*T*) was measured by thermocouples such as chromel - alumel, located at different distances from the weld. The structure was examined under an Epiquant light microscope at 50-500 magnifications. The preparation object for microstructure studies and estimation grain size of solid solution were determined by quantitative metallographic [13]. Micro hardness (H_μ), which was measured on a PMT-3 instrument, at indenter load 0.05N, was used as characteristic of strength micro-volumes of alloy.

4. Results and discussion

Measurement heating temperature edges near to the root of weld and estimation activation energy of the FSW process [4], determine the different nature effect on the rate heating of the metal from the ratio main technological parameters (Fig. 1a). According [2] it is logical to divide heating curve into three parts with qualitatively different character of temperature change. The first section of the curve, in proportion to speed of rotation work tool and pressing it to connecting edges, increases the temperature of alloy. In the second section, increase in temperature is accompanied by a constant level of pressing working tool, and in the third - by a decrease in *P*. Analysis nature of relation *T~(P,v)* (Fig. 1a) shows that the moment of deviation from proportional dependence, regardless of the speed rotation and force of pressing work tool, corresponds to the same temperature of 90 ^{o}C. In general, it should be assumed that at such a temperature conditions are achieved when the softening effect compensates for a considerable part of hardening alloy from plastic deformation. Thus, according [6], increasing temperature of hot compression, leading to the acceleration processes of diffusion mass transfer, actually determines ratio in development of these processes. Under these conditions, structural transformations are the result of development very complex processes dislocation redistribution, which, on the background of annihilation, are accompanied by formation dislocation polygonal cells with different types of sub boundaries and disorientation angles. According to the ratio $T_R \approx 0{,}4T_S$, where T_R and T_S -- respectively, the temperature of the recrystallization and melting

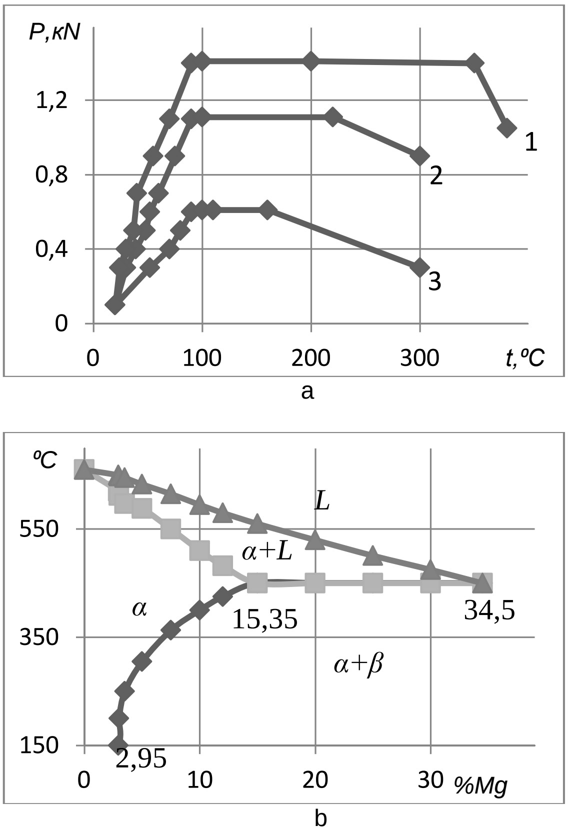


Fig.1. The ratio between temperature of surface, *P* and ν working tool (1 -800; 2 - 1250; 3 - 1600 min^{-1}) - (a) and part state diagram of *Al-Mg* - (b).

processes of metallic material [5], the temperature of deviation from the directly proportional ratio (Fig. 1a) coincides with temperature start of static recrystallization. However, for two-phase alloys, the development of recrystallization processes, including assembly (secondary), is largely determined by volume fraction of the second phase, its dispersion and its ability to interact with the metal matrix [20]. According to state diagrams (*Al-Mg, Al-Mn, Al-Fe*), the *AMg6* alloy consists of α - solid solution, with different concentration of chemical elements and particles of second phase: Al_2Mg (Fig. 1b), Al_6Mn and Al_3Fe. According analysis of these diagrams, the chemical compounds are interacting with the matrix, and the temperature interval of their existence determines that after heating above 275-285 ^{o}C (for *Mg* content 6,5%) must be fully dissolved particles (β-phase) (Fig. 1b), above 480 ^{o}C - Al_6Mn and Al_3Fe. On other hand, under actual conditions of development FSW the high heating rates, the temperature gradient and the existing inertia of system, should facilitate the shift moment of the beginning intense degradation of chemical compounds towards elevated temperatures relative to the phase equilibrium lines. But under optimal conditions for the development of FSW, a significant exaggeration of phase equilibrium temperature (according to various estimates, the temperature from 0.75 to 0.85 T_S [1-4] (for the tested alloy 380-470 ^{o}C) and acceleration of processes diffusion mass transfer are optimal for realization FSW process will inevitably lead to partial degradation of chemical compound particles.

Accelerating the diffusion processes along boundaries between phases and grains with large disorientation angles will result in a gradient of concentrations of alloying chemical elements and, first of all, *Mg*, in the micro volumes of matrix and increase hardening effect of solid solution state. In addition to heating temperature, an additional effect on the state of hot crimp action matrix should be expected. Indeed, in the course of development of super plastic deformation from the action of rod and shoulder of working tool FSW, maintaining a certain ratio between the creation and annihilation moving dislocations, while maintaining their total number in the system, sliding along the grain boundaries [11], become an additional factor in enrichment of matrix alloying elements. On this basis, the development structural processes in metallic matrix at formation of a welded joint at FSW should be accompanied not only by the influence of grain size, but also by the state of solid solution on micro hardness of alloy. If according to relation (Fig. 1a), moment of deviation from the proportional dependence is due only to beginning of the development of recrystallization processes in alloy matrix, then more complex structural transformations should occur at the site with constant clamping of the tool. In fact, to maintain the conditions of the super plastic deformation, it is necessary to maintain a certain relation between the rates of introduction and annihilation of dislocations, and their total number will determine thermodynamic stimulus for development of dynamic recrystallization processes. Moreover, presence particles of chemical compounds become an additional factor in maintaining the unaltered grain size of alloy matrix when the super plastic flow is reached. At static conditions development processes of secondary recrystallization in two-phase metallic materials, when the particles of the second phase are partially interacting with the matrix, the moment of migration the boundary of grain from the fixing points (particles second phase) can be taken as a criterion. As a result, there are areas in structure with the particle arrangement in the middle of the grains. For the alloy under study, simultaneous development of second phase particle coalescence processes and their partial degradation should reduce the effect of restraining migration of matrix boundaries upon the development of secondary recrystallization.

In general, the driving force of the secondary recrystallization is aimed at reducing surface energy of internal boundaries in the metallic material and is estimated by the relation [15]:

$$\Delta F_1 = 2\frac{\sigma_c}{d}, \qquad (2)$$

where σ_c is the surface energy of the grain boundary of the matrix, *d* is the average grain size. Another process that has the opposite orientation is due to influence of second phase particles on the grain boundary's ability to migrate during heating and holding at certain temperatures. In this case, the deceleration energy of the grain boundary motion from second phase is determined by the dependence [15]:

$$\Delta F_2 = \frac{3f\sigma_m}{D}, \qquad (3)$$

where σ_m is the energy of migrating boundary, the absolute values of which practically coincide with the value σ_c in relation (2) [15], *f* is the volume fraction second phase, *D* is the diameter particles. The condition of separation grain boundary from the particles becomes the equal that energies ($\Delta F_1 = \Delta F_2$). After the transformations, obtained ratio will determine dependence average grain size metallic material on the diameter particles and their volume fraction [16]:

$$d = \frac{2D}{3f} \qquad (4)$$

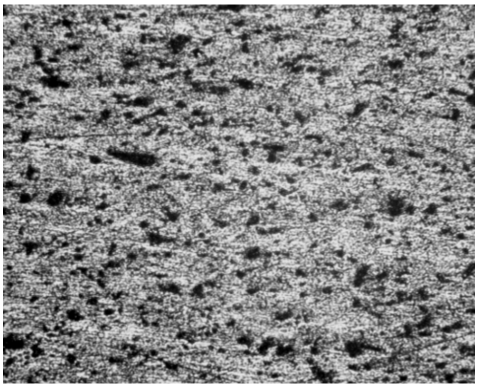
By relation (4), increasing dispersion of particles second phase and their volume fraction is accompanied by decrease in the grain size of matrix, with the coefficient (2/3) being a constant. In fact, the proportionality factor, determining the measure dependence *d* on *D* and *f*, is a characteristic dependent on *f*. Thus, for low carbon steels, the decrease in the volume fraction of cementite from the values of 0.1 - 0.08 is accompanied by a progressive deviation of the values calculated from (4) *d* from those obtained from analysis of the microstructure after development of secondary recrystallization. The aforementioned error can only be compensated by a change in the proportionality factor. On the other hand, the high rates of heating alloy from the action of the work tool, when increase in temperature is accompanied by the appearance high gradient of temperature in thickness of connecting edges, the moment of accelerated dissolution chemical compounds will inevitably be shifted to higher temperatures than at isothermal condition. On this basis, in addition to fulfilling conditions of propagation plastic deformation along the thickness of the connecting edges at the FSW, there is an additional factor of influence from the residual particles second phases on processes of structure formation in alloy matrix. Moreover, given the dissolution of second phases upon heating, it is expected that the concentration of chemical elements in solid solution will be influence on plasticity of the alloy. By extrapolating dependence (curve (2) of Fig. 1a) for the temperature range 330-360 ^{o}C , it can be determined that an increase in deformation temperature under the shoulder is accompanied by decrease in the level of deforming force compared to second section (*P* = *const*). The above-mentioned nature of change *P* can be considered as a tendency in reaching conditions of super plastic deformation at FSW. The obtained conclusion is in agreement with the known experimental data [1-5]. Indeed, in most studies, the moment of reaching conditions of super plastic deformation is a sharp decrease in strain force (stress). According to relation (1), such a requirement can be fulfilled only by obtaining microstructures with an equal dimension of phases, at the level of 3-5 μm. Achieving maximum plasticity will be determined by the ability to maintain the unaltered dispersion of structure as a whole. After forming the weld using the FSW technology, the studies determined qualitative changes of the microstructure depending on temperature propagation of plastic deformation (Fig. 2). At state on start of FSW, the alloy had a grain size about 3-4 microns. In the implementation FSW, development of plastic deformation processes is accompanied by the quite expected occurrence of temperature gradient in thickness of connecting elements. This is due to the different distance between micro volumes alloy and working plane of the tool shoulder. Given the very high sensitivity of the process development super plastic deformation in metallic materials to constant of maintaining temperature and deformation parameters, their relatively small deviations from optimal values are accompanied by a sharp decrease in alloy plasticity. To estimate of separate contribution from the boundaries with large angles of disorientation and the state of solid solution to resistance of the metal to small plastic deformations, we use the Hall-Petch type relation [5], which in its original form looks as follows:

$$\sigma_T = \sigma_i + k_y d^{-0,5}, \qquad (5)$$

where σ_T is the yield stress of alloy, σ_i is stress of friction crystal, k_y is the angular coefficient. The implementation relation (5) after replacement of yield stress at different degrees of deformation [17], for alloys with different dispersion and morphology second phase [18,19] indicates the possibility of its use for analyzing effect plastic flow of FSW on grain size by of micro hardness measurements. Given the lack of a clear boundary in structure between the three zones (Fig. 2b), it was decided to analyze for only two zones with guaranteed temperatures of 330 and 360 ^{o}C . After determining average grain size of alloy matrix in micro volumes, with the specified temperatures and appropriate micro hardness measurements, dependence was constructed and the value of stress used was $H\mu$:

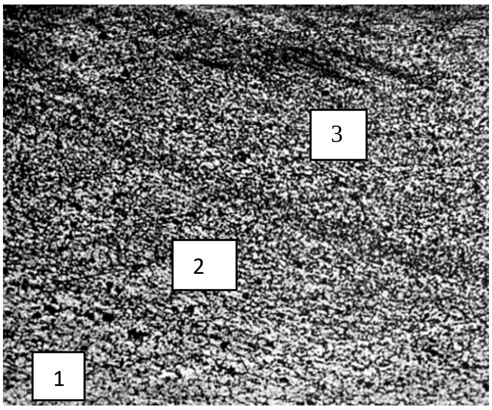
$$H\mu = H\mu_i + k_y d^{-0,5}, \qquad (6)$$

where the characteristics $H\mu_i$ and k_y have the same interpretation as for equation (5). The result of paired application $H\mu$ against the corresponding values of *d* is shown in Fig. 3. The fulfillment of this relation indicates that major contribution to the change $H\mu$ is determined by grain size of alloy matrix. The presence of second phase particles has an additive contribution, due to their location mainly along the grain boundaries with large disorientation angles. The fact is when the particles of second phase have a forced arrangement in the middle of the grains, the relation (5) is broken due to transition of role main structural element from grain diameter to the distance between particles [12]. Estimating parameters of equation (6) determined that with increasing heating temperature from 330 to 360 ^{o}C , contribution to the overall level of micro hardness from the state of solid solution ($H\mu_i$) decreases from 400 to 130MPa, and the resistance of propagation deformation from presence in structure boundaries of grain with large angles disorientation (k_y) will increase more than twice: from 2.5 to 6 $N \cdot mm^{-1,5}$. Given the nature of change in the parameters of equation (6), it becomes possible to determine the separate contribution of structural components in achieving conditions of super plasticity. As the heating temperature of alloy increases, the hardening effect of solid solution decreases, and effect of presence in structure the grain boundary with large disorientation angles increases. Moreover, comparative analysis of micro hardness for the same grain sizes but at different temperatures of plastic deformation is of particular interest. Considering that as deformation temperature decreases, the effect on flow stress from the development of deformation hardening will increase [18], but the degree of softening metal during the holding time (at elevated temperatures) after the deformation is completed will be greater [32]. Indeed, according Fig.4, for a grain size of 8 μm ($d^{-0,5} = 11mm^{-0,5}$) after an FSW in micro volume with temperature of 330 ^{o}C , H_{μ} after cooling it is less than 700MPa, and for a volume with 360 ^{o}C it is approximately 15% higher (H_{μ}^{330} p H_{μ}^{360}). For a range of relatively large grain sizes, a qualitatively different ratio should be expected. Extrapolation to a grain size of 28 μm ($d^{-0,5} = 6mm^{-0,5}$) gives a micro hardness of 520MPa for a temperature of 330 ^{o}C , and for a volume with a



a

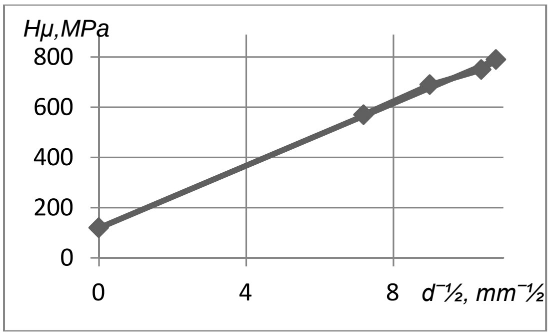
b



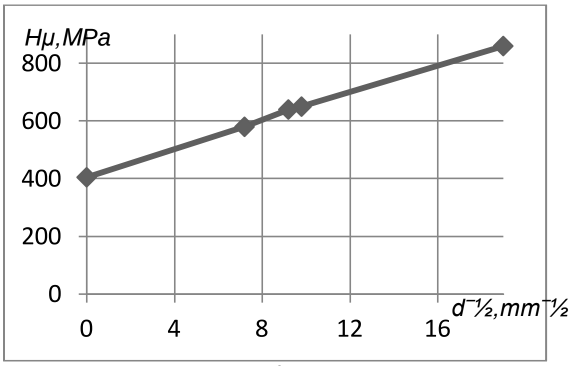
c

Fig.2. The structure of alloy in the derivative state (a) and the region of intensive mixing at FSW (ν =1250 min^{-1}) (b, c). Alloy heating temperature: (1) - 330, (2) - 345, (3)- 360 ^{o}C . Magnification: a - 500; b - 50; c - 175.

temperature of 360 ^{o}C, 480MPa (H_{μ}^{330} f H_{μ}^{360}). The existence of given micro hardness values for two temperatures and grain sizes can be considered as an estimation possibility of influence strain hardening processes in reaching conditions of super plastic flow Considering that as the size of ferrite grain low carbon steels and single-phase alloys [17] increases, the



a



b

Fig.3. Influence of grain size α - solid solution on micro hardness, depending on micro volumes with temperature alloy (a -360 ^{o}C, b - 330 ^{o}C).

parameters of strain hardening increase [18], it becomes clear the necessity of forming structure with a fine grain as a derivative component in the general problem of development super plastic flow. The second requirement is to maintain a constant predetermined ratio between strain rate and temperature [11, 12]. According to the obtained research results (Fig.1, 3), the ratio of technological parameters (velocity and temperature of deformation) should in reality correspond to minimum contribution from the processes of strain hardening during development of super plastic flow. Such a generalization actually involves the need to form over fine grains and maintain a constant number of dislocations to propagate of plastic flow due to the defined temperature-strain ratio. At the same time, the contribution from state of solid solution (solid solution hardening) to which insufficient attention is paid should be taken into account as an additional factor. In general, when forming requirements to achieve over super plastic flow in metallic materials, in addition to the known ones (structure with a fine grain and a certain ratio between temperature and strain rate), the effect of solid solution hardening should be taken into account. Thus, it becomes possible to formulate, more generally, requirements for the development of super plastic deformation - this is to minimize effect of development of strain hardening processes.

5. Conclusions

1.According to the results of researches, the additive character influence of solid solution state and grain boundaries with large disorientation an angle is determined when the conditions over plastic flow are reached.

2. At friction stir welding, the condition over plastic flow is achieved by reducing the effect of solid solution hardening and increasing contribution from boundaries fine grains.

6.References

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