Mechanisms of formation of the structure of welded joints, performed by friction stir welding

R A Rzaev[1], O M Alykova[1], V V Smirnov[1], A P Kanavin[2,3], I N Zavestovskaya[2,3]

[1]Astrakhan state university, Astrakhan, Russia
[2]National Research Nuclear University MEPhI Moscow Engineering Physics Institute, Moscow, Russia
[3]Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
E-mail: radmir.82@mail.ru

Abstract. The analysis of welded joints of structural materials is carried out. As a result of this, in addition to the traditionally formed zone of thermal influence (HAZ), a zone of thermal deformation influence is formed in the near-seam zone, located between the welded nugget and the HAZ. The welded nugget joints in FSW is formed in the regime of structural superplasticity (SP). The structure of the welded nugget has a sheared band structure in the form of an "onion pattern" consisting of a large number of lamellas forming shear bands under the influence of a movable welding tool. The attainment of the superplastic state (SPS) during the formation of the welded nugget is ensured by the stepwise flow of various mechanisms of plastic deformation in the regime of simple, collective, anomalous dynamic recrystallization, prepared by dynamic return processes, polygonization with transition to postdynamic recrystallization by the mechanisms of Bailey-Hirsch, Kahn-Burgers-Taylor. For the group of metals and alloys with polyformism (high-alloy steels of different structural classes, Ti- alloys), SPS is supported additionally by recrystallization by twinning (copper, austenitic steel and other structural classes, Ti and its alloys) and as a result of phase transformations of alpha-gamma or alpha-beta phases).
Keywords: friction stir welding; aluminium alloy; copper alloy; the welded nugget; heat affected zone; thermal- deformation affected zone; recrystallization; superplasticity.

1. Introduction

The main volume of production of welded structures from ferrous and non-ferrous metals and alloys is accounted for by methods of fusion welding (FW) using mainly arc energy sources [1, 2]. However, despite significant amounts of use in welding production, this group of welding methods has significant drawbacks that adversely affect the properties and performance of welded joints.Since its publication in 1991. patent [3] of Great Britain, an alternative to SPL - a solid-phase method of friction stir welding (FSW). Outside the interests of this development were studies on the disclosure of the mechanisms of formation of welded joints in a simillar and, especially, in dissimillarcombinations.In the framework of the further development of the STP method, the purpose of this work is to disclose the main mechanisms responsible for the formation of the structure of the welds (core) of welded joints made by the FSW method in the structural superplasticity (SP).

2. Materials and methods of research

The samples were welded on a 6T80Sh model vertical milling machine equipped with a set of welding tools for welding a specific metal of a given thickness, specialized equipment and the possibility of stepwise (smooth) control of mode parameters, including the tool deflection angle from the vertical.

The equipment used in the course of research to assess the quality of welding and the structure of welded joints zones is given below with reference to a specific research method.

Microstructural analysis was performed by optical light microscopy on microscope a Leica DMI 5000 M.Microhardness was measured on samples, the surface of which was previously subjected to mechanical grinding and polishing, and was slightly etched to reveal the structural orientation of the zone boundaries.

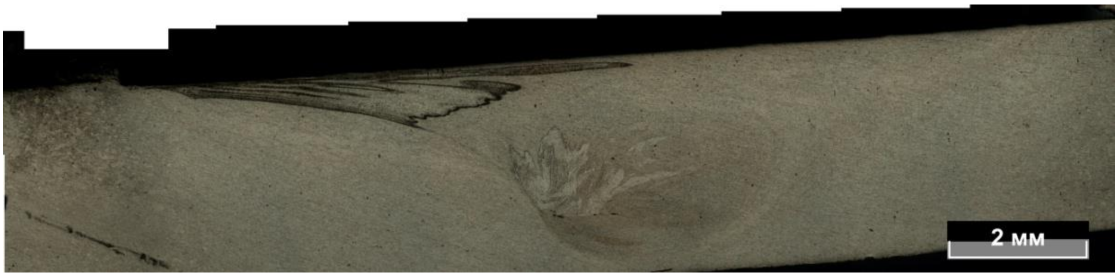
The hardness of welded samples was determined by the Vickers method on instrument a Vuehler Micromet-5103, with a load of 100 g and a holding time under load of 10 seconds. Processing of prints from a pyramidal diamond tip - indenter after removal of the load and the calculation of microhardness were performed in the program "Omnimet Imaging System".

3. Results and discussion

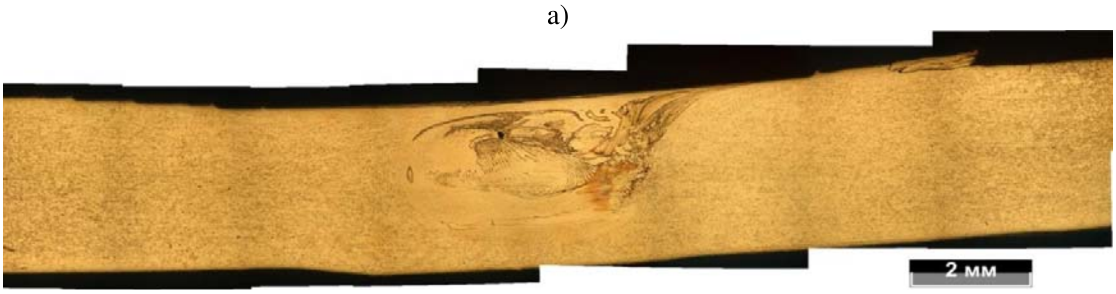
At the STP after the introduction of the rotating tool pin into the surface layers of the materials being welded, in the first 10-15 seconds of the process, the pin and the end of the shoulder will rub at the contact point of these parts of the tool with the edges of the metals being welded.

At the structural-microscale level, surface grains are involved in plastic deformation, which is realized due to the sliding movement of lattice dislocations due to the deformation gradient created by the welding tool [4]. However, in large-crystalline metals most dislocations are blocked by the Cottrell and Suzuki atmospheres, as a result of which their start is difficult and plastic deformation sources require sources of mobile dislocations, which can be high-angle grain boundaries — their triple joints.

Due to the deepening of the tool rotating and moving along the edges of the pin, the thickness of the welded plates forms the formation of several localities of plastic strain, and the mesozone expands to the entire cross section or thickness of the parts to be welded (Fig. 1).



a)



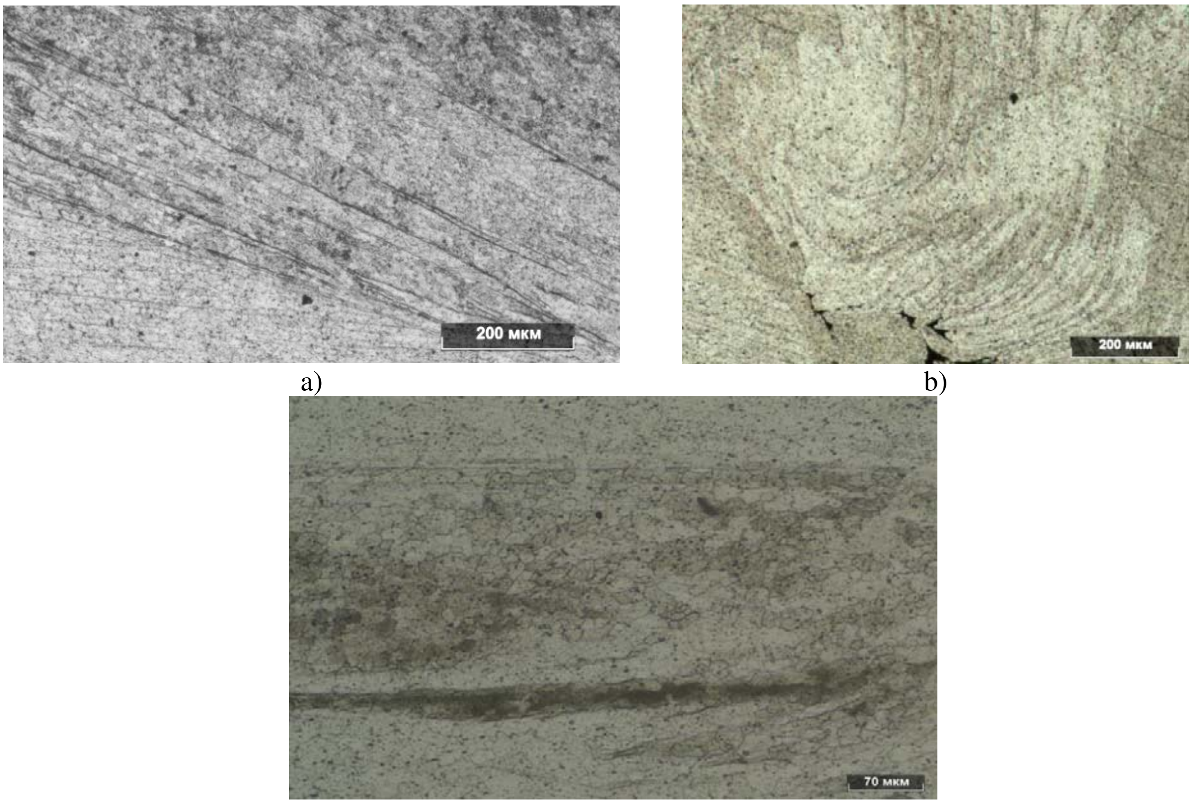
b)

Figure 1. Macro- cross section of welded joints: a-aluminum AD1; b-copper M1 alloys.

In accordance with the concept [4] of physical mesomechanics, according to which a vortex mechanical field is formed in a solid deformable body [5], deformation carriers are volumetric mesoeffects moving according to the “shift – rotation” scheme of large grains due to the involvement of smaller grains with the formation of vortices and metal flows in the SPS in the form of lamellae (Fig. 2).

At the mesoscale level, such zones against the background of a shear laminar flow have the form of turbulent perturbation zones (Fig. 3). Metal Physics Research of the fine structure in the lamellae of shear bands in the NW at the FSW AD1 (Fig. 4a), M1 (Fig. 4b), 12X18H10T (Fig. 4c), and the VT1 alloy (Fig. 4d) indicate their fine-grained structure.

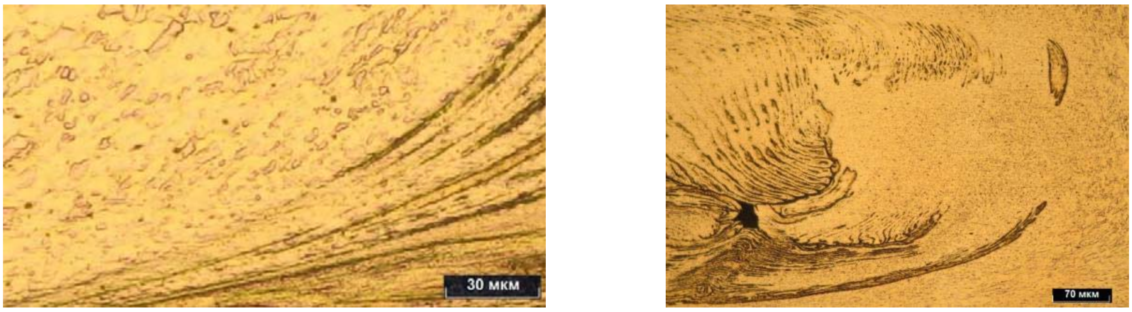
The microhardness values of grains (Fig. 5) change due to the presence in them not only of a large number of boundaries of smaller grains, but also of an increased density of lattice dislocations generated by the shear and generated by triple junctions grain.



a) b)

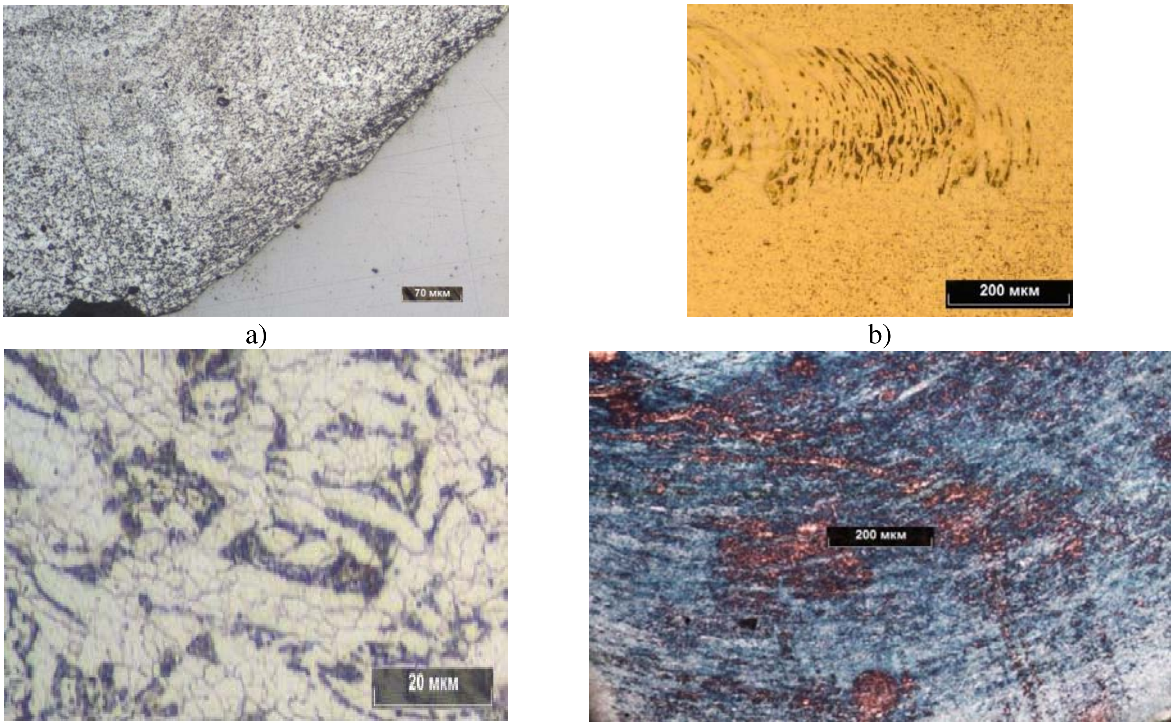
c)

Figure 2. Micro- cross section of the join of aluminum alloy AD1 with FSW: a - laminar flow from the shoulder; b - turbulent flow from the lower part of the pin, with lamellas divided into micrograin; c- is the central part of the WN with a classical recrystallized structure by the mechanism Bailey-Hirsch and the peripheral part by the mechanism Kahn-Burgers-Taylor.



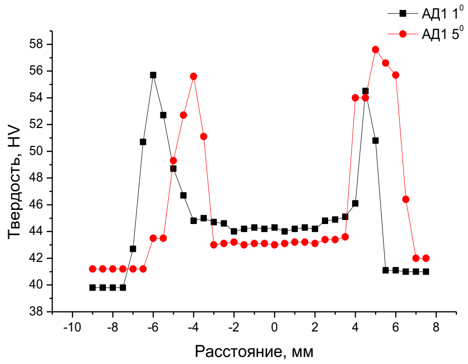
a) b)

Figure 3. Macro- cross sections of the joint of a copper alloy (M1) with a FSW a-laminar flow from the shoulder, areas of post-dynamic recrystallization in part by the mechanisms of Bailey-Hirsch and Kahn-Burgers-Taylor; b - turbulent flow in the lower (root) part of the joint.

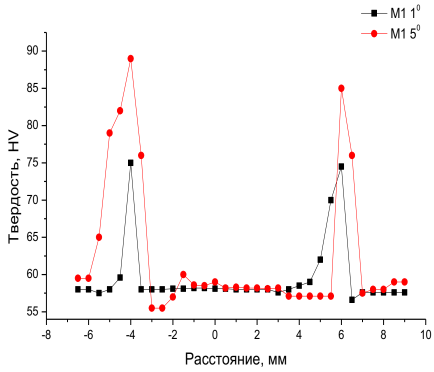


a) b) c) d)

Figure 4. Differentpartsoftheweldnuggetofweldedjointsa) - AD1; b) - M1; c)- steel 12X18H10T; d) - BT1 (therootzone)



a)



b)

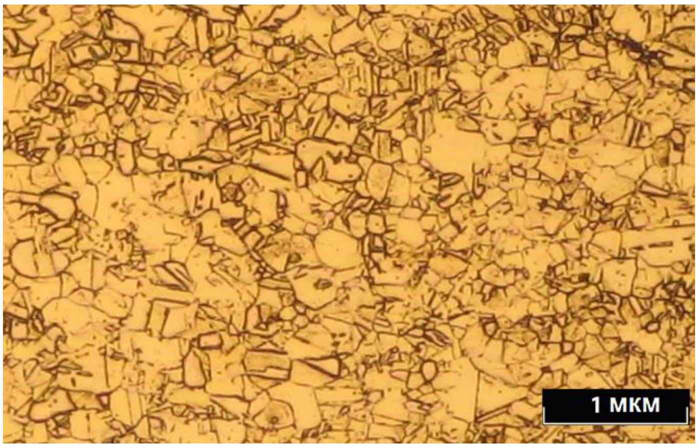
Figure 5. Distributionofmicrohardnessinthecross-sectionofweldedjoints: a-aluminumalloyAD1 (toolangle $1^0$and 5^0), b-copperalloyM1 (toolangle $1^0$and 5^0).

At the microscale level, for the majority of structural technically pure metals, the main contribution to the SP is made by the processes of intragranular slip of lattice dislocations (78% in fine crystalline aluminum, 91% in coarse crystalline) [7-10], and already on mesoscale in thermal pumping conditions by FSW, about 20% to achieve the joint venture brings grain-boundary slippage, activated by grain-boundary diffusion along mobile boundary dislocations of orientational mismatch. In the process of shearing - rotation of the grains, mobile lattice dislocations are captured by moving boundaries, their dissociation into separate vacancies, their concentration increases and the activation of diffusion creep and grain boundary slippage, which contributes to the achievement of superplasticity, can reach 30%.

In contrast to this ensemble of mechanisms of plastic deformation, at FSW Ti-alloys, stainless chromium-nickel steels of austenitic structural class, the transition to SPS is controlled by dynamic recrystallization processes as long as a sufficient level of mechanical stresses is maintained, which contributes to lowering the temperature of metal transition to a superplastic state (SPS) and due to the continuous inflow of heat from friction of the rotating parts of the tool (shoulder and pin) in contact with the metal being welded and of individual lamellae, is activated the initial stage of polymorphic ($\alpha \leftrightarrow \beta$) transformation, superimposed on a limited shear characteristic of plastic deformation by twinning [7, 9, 10]. Due to the natural fine grain size of titanium and its doped alloys, an important component of the plastic deformation of titanium in the FSW at the mesoscale level is grain boundary slippage, which, together with the crystallographic shifts that accompany the deformation of the α and β phases, is necessary to change their orientation: α-phases are prismatic slip by 10%, and β-phases by sliding or twinning already by 35–40%. Integrally, the total strain over the entire transformation cycle can reach 60% [9].

From research of domestic [11-15] and foreign researchers (Table 1), the SPS achievement rates for most structural metals and alloys differ on average by 30-50% in temperatures "T", an order of magnitude in strain rate "ε", by 20-30% in terms of the rate of sensitivity of the "m" to plastic deformation. For doped alloys characterized by elevated temperatures (more than 800 °C) of transition to SPS, dynamic recrystallization is characterized by a different mechanism: through the formation and growth of nuclei, migration of boundaries, and accompanied by the manifestation of structural superplasticity, grain boundary transformations and SP phase transformations.

The research data [11, 12-14] testifies to a significant effect of the energy of packaging defects on the plasticity characteristics during deformation of various structural metals and alloys. In materials with a high energy of stacking faults, dynamic recrystallization at the early stages occurs by the mechanism of formation of a developed subgrain structure. The appearance of small crystallites contributes to the development of intergranular slippage, the consequence of which is an increase in plasticity in the zone of formation of the WN [12]. At deformation temperatures corresponding to a noticeable increase in the mutual solubility of the metals or alloys being welded, dynamic recrystallization proceeds differently: according to the scheme of nucleation of the centers of crystallization and migration of grain boundaries. Redistribution of atoms of alloying elements in the matrix one way or another, their departure from crystalline structure defects into a solid solution can lead to the formation of a hardened border zone and impede the transfer of deformation from grain to grain, resulting in a local decrease in plasticity and the reduction of superplasticity. On the microstructure of copper welds, this phenomenon is well revealed in the form of the formation of chipping on the perimeter of grain boundaries, the formation of continuous rectilinear and wedge-shaped, curved or intermittent twinning boundaries (Fig. 6).



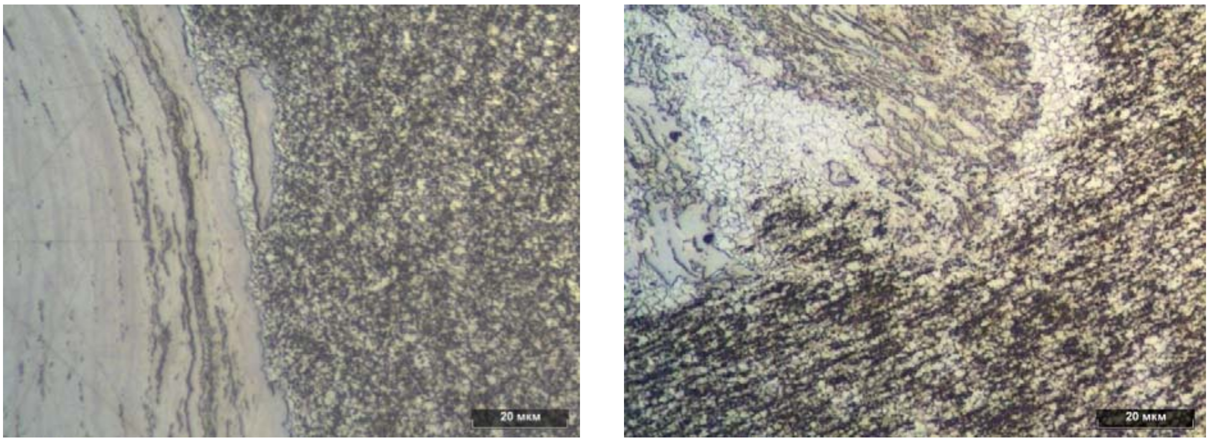
a)

Figure 6. Microstructure in the cross-section of a welded joint of a copper alloy M1 made with FSW with traces processes of dynamic recrystallization by the mechanisms of Bailey-Hirsch, Kana-Burgers-Taylor, areas of anomalous recrystallization, recrystallization by twinning under deformation influence of the tool on copper..

This development of processes is typical for materials with low energy packaging defects (an alloy based on copper, nickel, titanium, austenitic, ferritic, duplex nickel-chromium steels) or at moderate temperatures for materials with high energy packaging defects (aluminum), are not activated provided that the processes of dynamic recovery [14, 15], which block the development of dynamic recrystallization.

The possibilities of physicochemical separation of crystallites by the considered mechanisms are limited by the size of these crystallites, which, firstly, makes deformation processes and the associated accumulation of crystal defects difficult, and, secondly, requires diffusion of atoms over long distances, which cannot be realized under arising temperature conditions and time constraints characteristic of the process of FSW. Spheroidization and coagulation of phases are integral parts of the mechanisms of the processes developing in the FSW. They largely determine the level of mechanical properties of alloys, and, mainly, their plastic characteristics. The thermodynamic driving factor of these processes is the excess surface energy due to the large length of the interphase boundaries formed in the metal of the NW after dividing the extensive branched or flat lamella blocks of crystallites into individual particles (Fig. 7).

Journal of Physics: Conference Series **1439** (2020) 012025 doi:10.1088/1742-6596/1439/1/012025



a) b)

Figure 7. The welded nugget joint of austenitic stainless steel 18.Cr-10Ni-0.7Ti-0.6Mn-0.8Si-0.12C: a- wall section, b-bottom (root) areas (in the upper half of the figure, bright areas are observed in which the processes were activated of collective and anomalous recrystallization).

After crushing the crystals, develop spontaneous processes, first causing rounding of the sharp edges of the particles formed, and then their complete spheroidization (Fig. 7). The transition from the lamellar form of particles to spherical reduces the value of the specific surface per unit volume and, therefore, reduces the Gibbs energy level of the system. Further temperature effects contribute to the development of processes not only the spheroidization of particles, but also their coagulation, since the minimum free energy in a heterogeneous system will have structural areas with the largest crystallites that are capable of growing, while the smallest crystals will dissolve in the surrounding solid solution.An indispensable element of coagulation is the diffusion mass transfer of atoms of the alloying components of the alloy from dissolving small particles to growing large ones. The peculiarity of the course of these processes in the FSW is a higher speed of their development and greater completeness of their implementation. This is due to the fact that at FSW an increased number of defects crystal structure (vacancies, dislocations) occurs, which increases the diffusion mobility of atoms, which determines the development of mass transfer, both during spheroidization and coagulation.

The coagulation processes are shifted in time, as well as in temperature and number of cycles in the direction of large values of these parameters. This is due to the need for the diffusion of atoms of the alloying elements through the solid solution over long distances, commensurate with the distances between the particles or grains. With the spheroidization of particles, these diffusion paths are comparable with the size of the particles themselves, which is at least an order of magnitude smaller than with coagulation. In addition, in the case of spheroidization, accelerated diffusion along the interfacial surface is possible, whereas during coagulation, diffusion must occur through the solid solution. Spheroidization of particles, like their physicochemical division, almost always increases the ductility of alloys. Coagulation is ambiguous. Excessive growth of particles can cause a decrease not only in strength, but also in ductility, causing embrittlement of the weld metal. Therefore, a high complex of properties of welds made by FSW can be achieved only with an optimal ratio of the processes of breaking and restoring new interatomic bonds, which are realized during the formation of compounds of FSW in the solid phase.

To start the above mechanisms, the mode must be corrected parameters of the FSW, creating conditions for the formation of welded joints in the mode of structural superplasticity characteristic of the particular being welded material, in approximation to the temperature-deformation parameters given in Table 1.

Table 1. Characteristics of materials to be welded at FSW.

Alloy	Grain size in original condition	Meltingtemperature (T_{max}), °C	Temperaturetransition of SP, ($T_{сп}$) °C ($T_{max}/T_{сп}$)	Temperaturerecrystallization, (T_{rc}) °C	The manifestation indicators of SP: elongation, coefficient of speed sensitivity, the rate of deformation abilities.
AD31, AD1	NCC (about 0.35 microns)	565	270 (0,48)	266	m=0,33-0,43; n=2,0-2,5 at “ε“ =8×10^{-3}
M1	NCC (about 0.4 microns)	1083	570 (0,25)	250- 300	m=0,33; n=2,0-2,5 at “ε“ =8×10^{-3}
VT1	NCC (upto 100 nm)	1820	700 (0,38)	600	m=0,22-0,5; n=3,5-4,4 at “ε“ =8×10^{-3}
OT4-1	MKK (about 1 micron)	1760	860 (0,49)	880	m=0,4; n=2 at “ε“ =8×10^{-3}
18.Cr-10Ni-0.7Ti-0.6Mn-0.8Si-0.12C	2-20 microns	1450	780 (0,51)	800	tobreak 220%, at “ε“ =3×10^{-3} , m=0,27; n=2

4. The conclusion

1. The core of welded joints made in the solid phase of the FSW is formed by a rotating tool in the mode of structural superplasticity due to the occurrence of corporate recrystallization processes and phase transformations.

2. The achievement of the SPS during the formation of the WN in the solid state is ensured by the gradual flow of various plastic deformation mechanisms in the mode of simple, collective, anomalous dynamic recrystallization prepared by dynamic return and polygonization processes with a transition to post-dynamic recrystallization using the mechanisms Bailey-Hirsch, Kahn-Burgers-Taylor.

3. In case of FSW of metals and alloys possessing polyformism (high-alloy steels of different structural classes, Ti-alloys), the SPS is supported additionally due to recrystallization by twinning under the action of shear deformations (copper, austenitic and other structural steel, Ti and its alloys) and as a result of phase transformations alpha gamma or alpha betta phases).

References

[1] Nerovny V.M. 2016 *Theory of welding processes.* (Moskva: Publishing office BMSTU) p. 702.

[2] Zorin N. Ye., ZorinYe.E. 2018 *Material Science of welding. Fusion welding*. (Publishing office: Lan) p. 164.
[3] Thomas W. M., Nicholas E. D., Needham J. C. et al. *Friction stir butt welding*. Pat. 5460317 US. Publ. 1995.
[4] IshchenkoA.Ya., Podelnikov S.V., Poklyatsky A.G. Welding of aluminium alloys (directions of research conducted at PWI). 2007 *The Paton Welding Journal* №11, pp. 6- 10.
[5] Makarov S.V., Plotnikov V.A., 2015 *Acoustic wave correlation of elementary deformation acts under high-temperature deformation of metals and alloys* ([Text]: monograph. Publishing house of Altai state. University) p. 215.
[6] Smirnov O.M. Superplasticity of nanocrystalline and amorphous materials. 2010 *Promising materials* p. 228– 241.
[7] Babareko A. A., Egiz I.V., Khorev A.I. Superplasticity of titanium alloys of different classes 1995 *Metal Science and Heat Treatment of Metals* No6, p. 30- 35.
[8] Bogolyubova D.N., Gvozdev A.E., Pantyukhin O.V. Investigation of the regularities of manifestation of the effect of dynamic recrystallization in metals 2011 *Izv. Tula State University. Ser. Metal science* Issue 4 p. 276- 286.
[9] Galeyev R.M., Valiakhmetov O.R., Salishchev G.A. Dynamic recrystallization of coarse-grained titanium alloy VT30 in the ($\alpha + \beta$) field. 1990 *Metals* №4 p. 97– 103.
[10] Nesterova E.V., Rybin V.V. Mechanical twinning and fragmentation of technically pure titanium at the stage of developed plastic deformation 1985 *FMM* V. 59(2) p. 396- 406. (In Russ.).
[11] Nandan R., DebRoy T., Bhadeshia H.K.D.H. Recent advances in friction-stir welding - process, weldment structure and properties 2008 *ProgressinMaterialsScience* V. 53 p. 980-1023.
[12] Zaikina A.A., Levikhina A.V. Features of fracture of welded joints obtained by friction stir welding with static stretching 2014 *Sovremennyeproblemynaukiiobrazovaniya* No5 p. 239.
[13] Kolobov Y.R., Grabovetskaya G.P., Ivanov M.B., Ivanov K.V., Girsova N.V. Regularities of structure evolution of metals and alloys during severe plastic deformation and superplastic flow. 2003 *VoprosyMaterialovedeniya* №1 (33) p. 184 – 191.
[14] KolobovYu.R., Lipnitsky A.G., Ivanov M.B., Nelasov I.V., Manohin S.S. Researchs of the thermal stability of the titanium microstructure formed by the action of intense plastic deformation. 2011 *Izv. universities. Physics* №8 p. 77-95.
[15] Kaibyshev R., Malopheyev S. Mechanismus of dynamic recrystallization in alumininum alloys 2014 *MaterialScienceForum* v. p. 784– 789.
[16] Biront V.S. 2007 *Theory of heat treatment of metals. Annealing.* (Krasnoyarsk. SFU ITs MiZ) p. 234.