FRICTION STIR WELDING OF COMPOSITE, GRANULATED AND QUASICRYSTALLINE ALUMINIUM ALLOYS

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Structural peculiarities and mechanical properties of welded joints on strengthened aluminium alloys are studied. It is shown that the use of friction stir welding does not lead to any substantial phase-structural changes in the weld metal and adjoining regions.

Keywords: *friction stir welding, granulated aluminium alloys, composites, meta-stable quasicrystalline particles*

One of the important trends in current engineering is decrease in weight and dimensions of structures with retention of their functional capabilities. Particular emphasis is placed on these requirements in manufacture of aircraft and spacecraft engineering products, overland and water transport. During the last decades this problem has been addressed through a wider utilisation of new high-strength aluminium alloys with high indicators of specific strength, elasticity modulus, corrosion resistance and resistance to propagation of fatigue cracks in the process of operation. However, the possibilities for further improvement of properties of commercial aluminium alloys produced by the traditional methods of casting and subsequent rolling have practically been exhausted. Therefore, a substantial improvement of performance of parts can be achieved by manufacturing them from qualitatively new advanced materials based on aluminium alloys. Such materials include modern granulated aluminium alloys strengthened by dispersed intermetallics that contain oversaturated solid solution of transition metals, composite materials reinforced by dispersed nanosized particles, and alloys strengthened by meta-stable quasicrystalline particles produced at high solidification rates. However, realisation of potential capabilities of such advanced materials in fabrication of efficient welded structures depends to a considerable degree upon the quality of their joining.

Table 1. Composition and tensile strength of 2 mm thick sheets of composite materials based on aluminium alloys

Matrix alloy	Content and composition of reinforcing particles	Sizes of reinforcing particles, μm	Distance between reinforcing particles, μm	Tensile strength σ_t, MPa
AMg5	27 % Al_2O_3	3–.15	3–20	340
AL25	25 % Al_2O_3	5–20	5–60	267
D16	20 % SiC	3–5	1–5	512
AL25	18 % SiC	5–15	3–50	278
AD0	7 % Al_2O_3	≤ 0.1	0.1–2.5	148
D16	20 % SiC	≤ 0.1	0.1–2.5	574

The purpose of this study was to evaluate the efficiency of application of friction stir welding (FSW) for production of sound joints on composite, granulated and quasicrystalline aluminium-base alloys.

Investigations were conducted by using some composite materials based on aluminium alloys with dispersed reinforcing ceramic particles of aluminium oxide Al_2O_3 or silicon carbide SiC (Table 1). These structural materials hold much promise owing to their high values of elasticity modulus, wear and corrosion resistance, and low values of specific weight and thermal expansion and friction coefficients [1, 2].

Structure of a composite material consists of matrix grains of an aluminium alloy, intermetallic inclusions and particles of a reinforcing phase, which are more or less uniformly distributed in the bulk of the matrix (Figure 1).

Fusion welding of composite materials causes complete melting of some of their volume in the zone of formation of a permanent joint under the effect of a high-temperature heat source, solidification of this volume resulting in formation of the weld. Reinforcing particles that remain non-melted are very non-uniformly distributed in the solidifying weld metal (Figure 2, *a*). Moreover, if in welding of composite materials reinforced with silicon carbide particles the temperature of metal heating exceeds 660 °C, their interaction with aluminium may result in formation of acicular inclusions of aluminium carbide Al_4C_3 (Figure 2, *b*). This leads to substantial deterioration of properties of the weld metal and, hence, of the welded joints.

Characteristics of composite materials are greatly affected by fractional composition and uniformity of distribution of reinforcing particles in the matrix, in addition to mechanical properties of a filling compound and matrix alloy, proportion of the volume contents of components, structure of composite castings and character of heat or thermomechanical treatment. Sizes of the particles determine both their in-

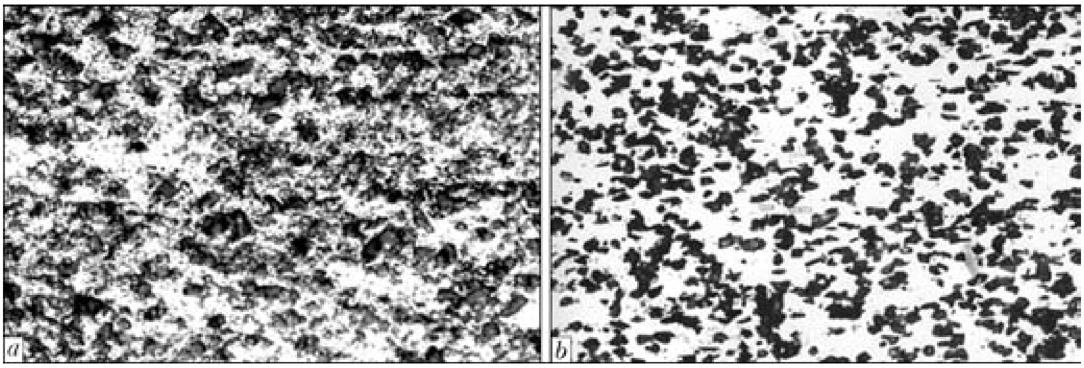

Figure 1. Microstructures of composite materials based on aluminium alloys D16 with 20 % SiC (*a* — ×600) and AMg5 with 27 % Al_2O_3 (*b* — ×400)

ternal structure and structure of interfaces with the matrix. Decrease in sizes of the reinforcing particles causes decrease in density of dislocations and level of internal stresses in the boundary layers. Elastic bending of the lattice at junctions of individual grains takes place in coarser particles, this inducing elastic stresses in these regions. In addition, increase in sizes of the particles leads to increase in density of their structural defects, quantity of twins and stacking faults [3, 4]. Therefore, composite materials with nanodispersed reinforcing particles of aluminium oxide Al_2O_3 or silicon carbide SiC are among the most promising structural materials for fabrication of efficient welded structures.

It is of critical importance that during welding of aluminium-base composites reinforced with the nanodispersed particles these particles be uniformly distributed over the entire volume of the weld metal and their accumulation be prevented. As shown by the investigations conducted, the solid-state FSW process can provide preservation of the initial nanodispersion of the reinforcing particles and degree of their distribution across the section of the weld at a level of the base material (Figure 3).

The efficiency of the solid-state FSW process was evaluated [5] also on granulated aluminium alloys 1419 (%: Al–2Mn–1Cr–0.6Ti–0.6Zr–0.6V), 1579 (%: Al–5.5Mg–0.3Mn–0.75Cr–0.8Zr–0.15Co) and 1995 (%: Al–3Mg–4.9Zn–0.28Mn–0.65Cr–0.21Ti) produced by the powder metallurgy methods. The level of doping of aluminium alloys with refractory transition metals, such as chromium, zirconium, titanium etc., can be substantially increased owing to a high rate of cooling of granules during solidification. The above metals form abnormally oversaturated solid solutions in solidification of the granules. Decomposition of such solid solutions taking place during further technological heating cycles results in formation of dispersed intermetallic compounds that provide strengthening of the alloys. Mechanical properties of the 2 mm thick sheets of these alloys are given in Table 2.

Results of experimental studies prove that in FSW of the investigated granulated alloys the minimal hardness of metal is fixed in the weld and zones of its transition to the base metal. Width of the weakening zone and value of the minimal metal hardness depend on the grade of an alloy. For instance, in welding of sheets of alloy 1419 with hardness *HRB* 86 (all measurements of hardness were made under load $P = 600$ N) the minimal hardness of the weld metal is at a level of *HRB* 75, while the width of the weakening zone is about 14 mm. In welding of sheets of alloy 1579 with hardness *HRB* 105, the minimal hardness of the weld metal is *HRB* 100, and the width of the weakening zone is 16 mm. Hardness of the weld metal produced in welding of sheets of alloy 1994 (*HRB* 112) is at a level of *HRB* 106, weakening taking place in a zone 20 mm wide.

Specimens of the FSW joints on these composite materials subjected to uniaxial tension fracture in the thermomechanically affected zone at the weld to base

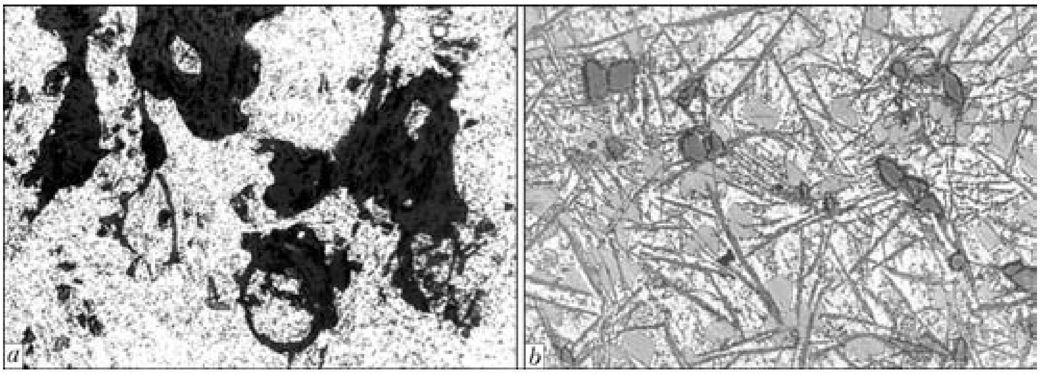

Figure 2. Microstructures of metal of the welds produced by fusion arc welding of composite materials based on aluminium alloy AL25 with 25 % Al_2O_3 (*a* — ×400) and 18 % SiC (*b* — ×600)

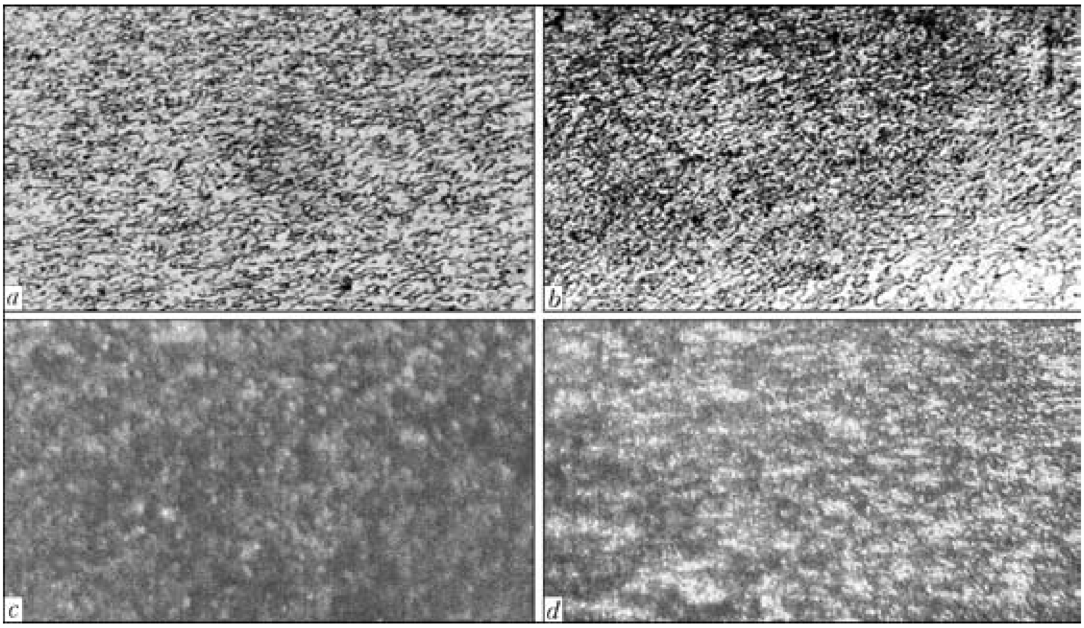

Figure 3. Microstructures of metal of the welds (*a*, *c*) and zones of their interfacing with the base material (*b*, *d*) in FSW of composite nanodispersed materials based on aluminium alloy AD0 with 7 % Al_2O_3 (*a*, *b* — ×400) and aluminium alloy D16 with 20 % SiC (*c*, *d* — ×200)

metal interface, which is characterised by formation of regions with certain structural differences. In this zone the weld nugget having a finely dispersed structure adjoins the base material, which was subjected to the thermal effect and changed the direction of its texture because of rotational and translational movement of the welding tool (Figure 4).

At the same time, no appreciable eutectic precipitations take place in interlayers between the grains. That is why strength of the friction stir welds on the granulated alloys is much higher than the welds made by TIG welding in argon atmosphere. For example, tensile strength of specimens of the solid-state welded joints on alloy 1419 is at a level of 255 MPa, this constituting 75 % of this characteristic of the base material (Table 3). Specimens of the FSW joints on alloy 1579 have tensile strength of about 354 MPa, and those of the FSW joints on alloy 1995 — 483 MPa, this making up 71 and 79 % of tensile strength of the base materials.

As shown by mechanical tests, in uniaxial tension the specimens with weld reinforcement produced by TIG welding in argon atmosphere using filler wire SvAMg63 fracture in the weld to base metal fusion zone. Tensile strength of such joints depends on the doping system of an alloy. For instance, the welded joints on alloy 1419 have tensile strength at a level of 243 MPa, those on alloy 1579 — 385 MPa, and those on alloy 1995 — 430 MPa.

Table 2. Mechanical properties of granulated aluminium alloys

Alloy grade	Tensile strength σ_t, MPa	Yield stress $\sigma_{0.2}$, MPa	Elongation δ, %	Bending angle α, deg
1419	340	280	14.0	115
1579	500	420	8.0	61
1995	610	530	8.5	22

Fracture of the specimens without weld reinforcement occurs in the weld metal having a cast coarse-crystalline structure (Figure 4). Moreover, particles of oxide inclusions and intermetallics formed as a result complete melting of the granules containing oversaturated solid solution of transition metals precipitate along the grain boundaries both in the weld metal and in the zones of its fusion with the base material. Such welds have low tensile strength. Tensile strength of the TIG weld metal on alloy 1419 is no more than 215 MPa, this making up 63 % of this characteristic of the base material. Tensile strength of the weld metal on alloy 1579 is 287 MPa, and that on alloy 1995 — 291 MPa, this being only 57 and 48 % of tensile strength of the base metal.

Structural peculiarities of the welds and their mechanical properties were also investigated in FSW of 1 mm thick sheets of heat-resistant aluminium alloy Al94Fe2.5Cr2.5Ti1 reinforced with meta-stable quasicrystalline particles [6]. The presence of quasicrystals with a size of 100–200 nm and an intermetallic that had no time to acquire the crystalline structure

Table 3. Tensile strength of welded joints on granulated aluminium alloys produced by TIG welding in argon atmosphere using filler wire SvAMg63 and by FSW, MPa

Welding method	1419	1579	1995
TIG welding (with weld reinforcement)	$\frac{246\text{–}233}{243}$	$\frac{391\text{–}379}{385}$	$\frac{436\text{–}420}{430}$
TIG welding (without weld reinforcement)	$\frac{220\text{–}208}{215}$	$\frac{290\text{–}283}{287}$	$\frac{297\text{–}287}{291}$
FSW	$\frac{257\text{–}253}{255}$	$\frac{357\text{–}350}{354}$	$\frac{490\text{–}478}{483}$

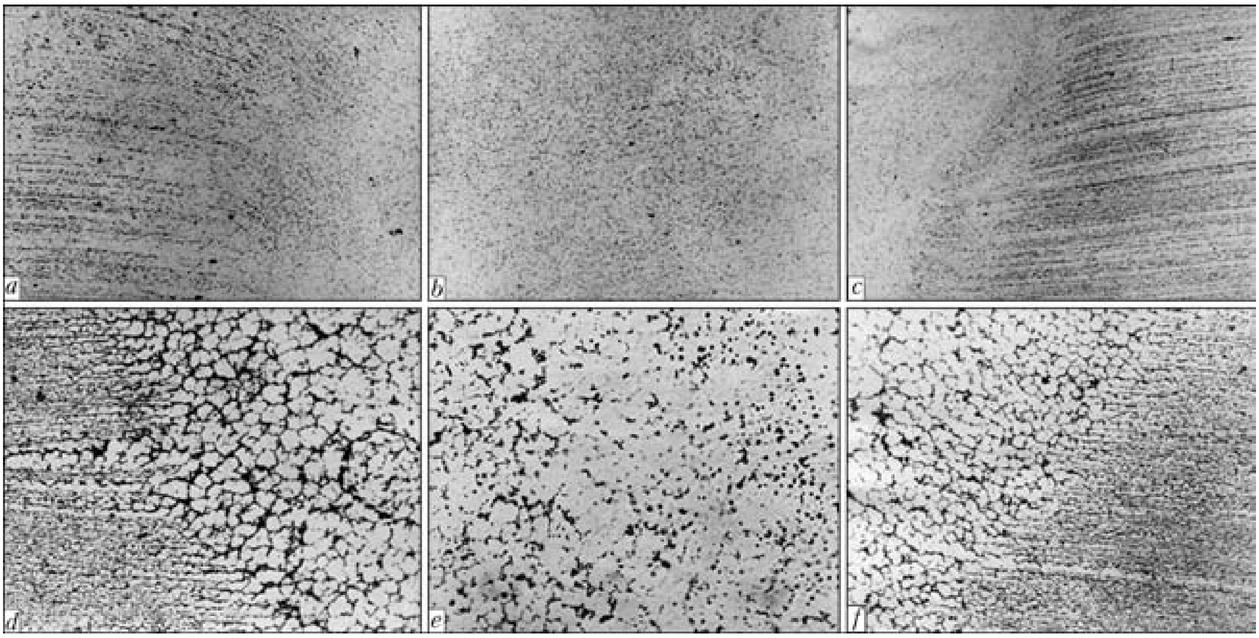

Figure 4. Microstructures (×400) of welded joints on 2 mm thick alloy 1579 produced by FSW (*a*, *c* — weld to base metal interfaces in the thermomechanically affected zone; *b* — weld nugget) and TIG welding in argon atmosphere using filler wire SvAMg63 (*d*, *f* — weld to base metal fusion zones; *e* — weld)

in this alloy provides tensile strength of a sheet equal to 585 MPa and elongation of 8.4 % at room temperature, and 345 MPa and 3.9 %, respectively, at a temperature of 300 °C. It is practically impossible to produce sound permanent joints on such a material by fusion welding. Firstly, when heated to a high temperature (above $0.8T_{\mathrm{melt}}$), the meta-stable quasicrystalline particles take the form of crystalline intermetallics, as a result of which the material becomes brittle and loses its strength and ductile characteristics [7]. At the same time, as the material is melted, the reinforcing particles precipitate from the aluminium matrix and prevent formation of a common weld pool and a continuous dense weld (Figure 5).

The conducted experimental studies showed that FSW, which is implemented in the solid state and does not change the phase-structural state of initial semi-finished products, is a promising method for production of sound permanent joints on such materials. As revealed by metallographic examinations, the mean size of grains of the α-Al matrix in the weld metal is approximately 200–300 nm, and that of quasicrystals is 100–200 nm, like in the base metal (Figure 6).

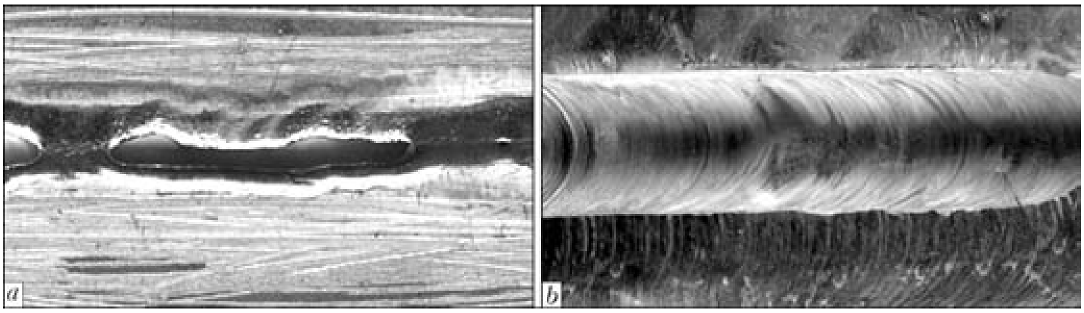

Figure 5. Appearance of the welds made by TIG welding in argon atmosphere (*a*) and FSW (*b*) on 1 mm thick aluminium alloy Al94Fe2.5Cr2.5Ti1

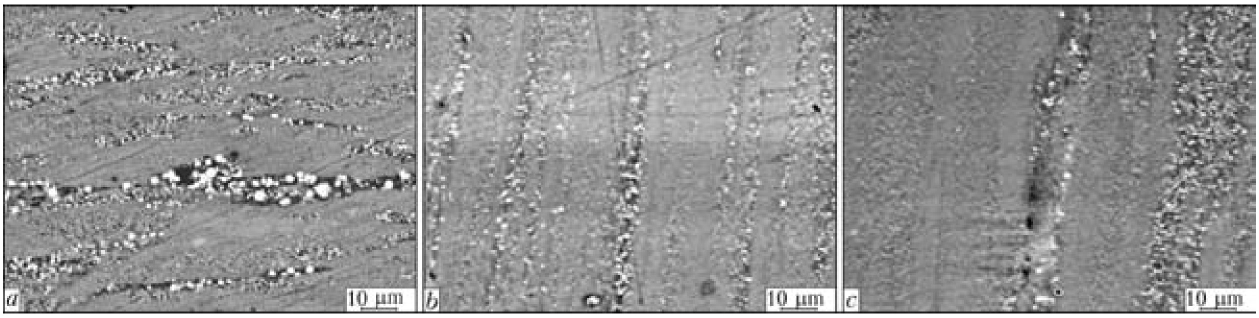

Figure 6. Microstructures of the base material in transverse (*a*) and longitudinal (*b*) directions and of the weld nugget (*c*) produced by FSW on 1 mm thick aluminium alloy Al94Fe2.5Cr2.5Ti1

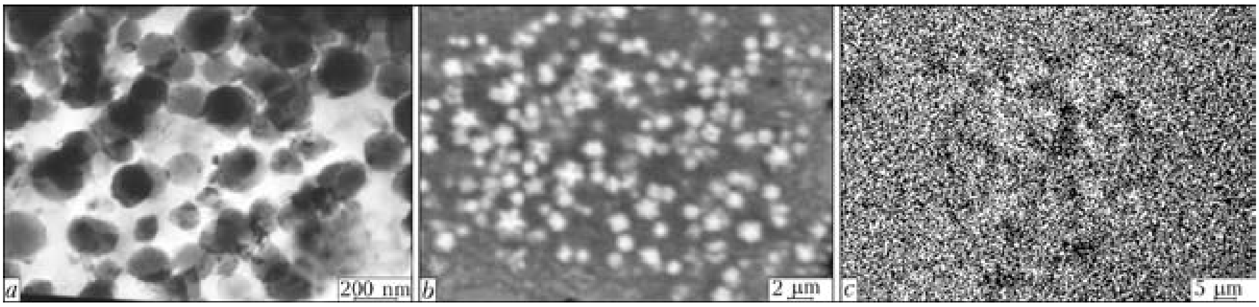

Figure 7. Images of quasicrystalline particles of intermetallic phase in light-field TEM picture (*a*), back-scattered electron SEM picture (*b*) and in characteristics X-ray radiation (*c*)

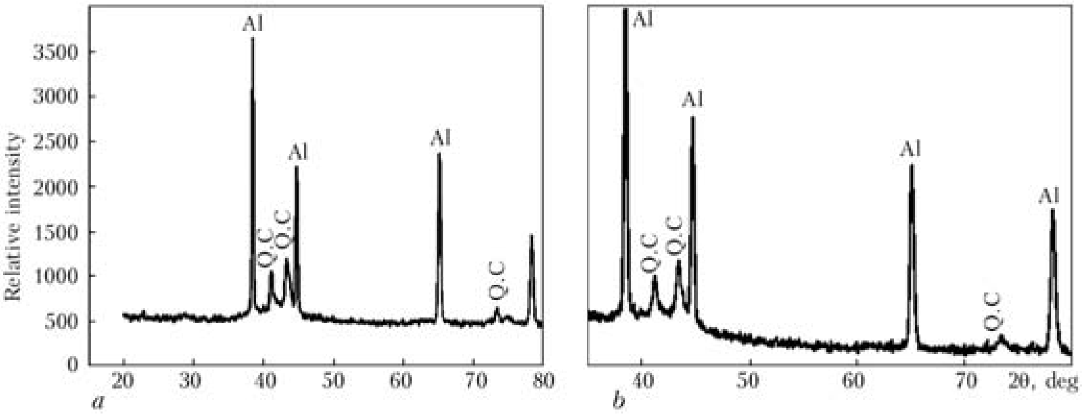

Figure 8. Fragments of diffraction X-ray spectrum of base (*a*) and weld (*b*) metals

Analysis of fine structure indicates that the reinforcing meta-stable quasicrystalline particles have a round shape, diffuse boundaries in the light-field image and characteristic herringbone contrast in the dark-field image both in the base material and in the welds produced by FSW (Figure 7). At the same time, the weld metal is composed of a uniform mixture of grains of the α-Al matrix and quasicrystalline particles.

The welding process does cause heating of metal to high temperatures. Hence, all of the reinforcing particles retain their quasicrystalline structure, which is confirmed by results of X-ray structure analysis (Figure 8).

The welding process results in reorientation of fibres in the thermomechanically affected zone at the weld to base metal interface, this reorientation being caused by the force effect exerted by the rotating welding tool moving along the joining line (Figure 9).

Mechanical tests with uniaxial tension of specimens of the FSW joints showed that their fracture at

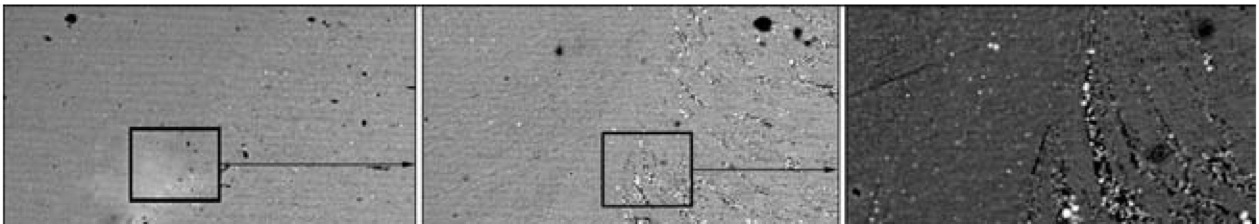

Figure 9. Microstructures of the weld to base material interface zone in FSW of 1 mm thick alloy Al94Fe2.5Cr2.5Ti1

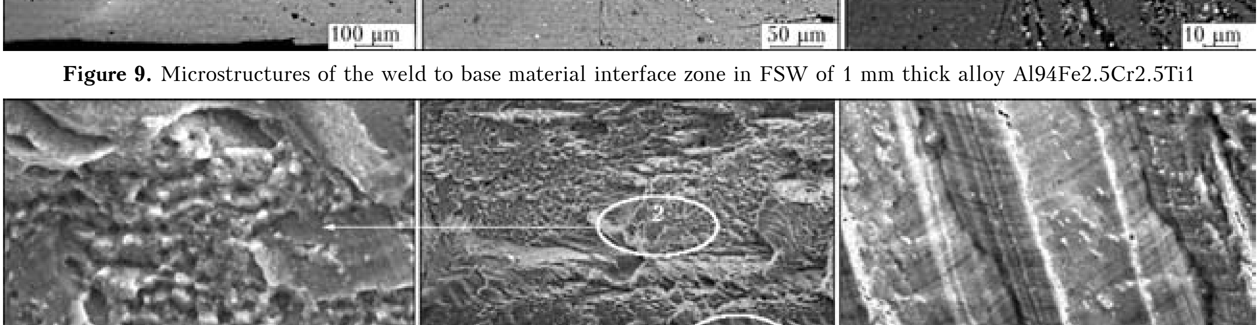

Figure 10. Microstructures of the specimen fracture surface and individual fracture regions

temperatures of 20 and 300 °C occurs in the zone of transition from the weld to base metal and propagates to the weld metal and thermomechanically affected zone (Figure 10). Recesses, which are indicative of a tough character of fracture of the specimens, can be easily seen on the fracture surfaces at high magnification.

Tensile strength of the joints is at a level of 370 MPa at a test temperature of 20 °C, and 197 MPa at 300 °C. The strength factor of the FSW joints is 0.63 at a test temperature of 20 °C and 0.57 at 300 °C. Elongation of the specimens remains at a level of 3.3 and 2.2 %, respectively, for the above test temperatures.

It should be noted in conclusion that due to formation of welds in the solid state, the FSW process allows the sound permanent joints to be produced on granulated, quasicrystalline and composite aluminium alloys without changing their phase-structural state. The granules containing oversaturated solid solution of refractory transition metals are uniformly distributed over the entire volume of the matrix in the weld metal, this providing tensile strength of such joints at a level of 70–80 % of that of the base material. No intermetallics are formed in the weld metal on aluminium alloy reinforced with the quasicrystalline particles, while the quasicrystals, the size of which remains within 100–200 nm, like in the base material, are uniformly distributed between grains of the α-Al matrix, thus providing welds with high strength and ductility values. No dissociation of the reinforcing particles is fixed in welding of composite materials, while their dispersion degree and uniformity of distribution in the weld metal remain at a level of the base material.

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FORCE EFFECT ON WELDED SURFACES INITIATED BY RUNNING OF SHS REACTION IN NANOLAYERED INTERLAYER

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The case of welding samples of titanium aluminide through nanostructured Ti/Al interlayer was used to calculate stresses arising in the surface layers of welded intermetallide samples, initiated by intensive heat evolution at running of the reaction of self-propagating high-temperature synthesis in the interlayer.

Keywords: *welding, nanolayered interlayer, reaction of self-propagating high-temperature synthesis, thermal stresses*

Studies [1, 2] show that an application of nanolayered foils based on elements forming intermetallides as interlayers significantly improves the conditions necessary for formation of solid phase permanent joints, i.e. heating temperature, delay time and pressure, applied for the joint obtaining, are reduced. Analysis of a diffusion zone of titanium aluminide based welded joint determined that its size increases 4 times in comparison with the diffusion zone, obtained in welding of intermetallide without the interlayer under similar conditions.

It is well-known fact that a reaction of self-propagating high-temperature synthesis (SHS), accompanied by intensive heat evolution, can be initiated in the process of heating. SHS reaction in Ti/Al foils, for example, took place in a mode of gas-free burning or heat explosion [3, 4] depending on initial temperature, thickness of the layers and their amount. Burning rate achieves 150 cm/s at 1100–1300 °C temperature. An intensity of heat evolution at running of SHS reaction, for example, in Ni/Al foils, can make 4 W/m^2. Such a pulse heat effect on the surface layers of welded materials can provoke in them appearance of the elastic stresses, besides local temperature increase, which also have influence on mass transfer