FRACTURE SURFACE MORPHOLOGY AT FATIGUE OF MIG-WELDED JOINTS OF AMg6 ALLOY

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Results of examination of structure of fracture surface on samples of MIG-welded joints of AMg6 alloy after cyclic tests with loading cycle asymmetry $R_\sigma = 0.4$ and $R_\sigma = -1$ are given. Peculiarities of morphology in different fracture regions have been revealed and mechanism of fatigue crack propagation has been established. It is noted that fracture of the welded joints at a microlevel is of a mixed and multi-site nature. High-frequency peening in a narrow AMg6 alloy weld to base metal transition zone using steel strikers provides formation of a smoother geometry of the weld to base metal transition zone and decrease in average values of the stress concentration factor.

Keywords: *arc welding, aluminium alloy, consumable electrode, welded joints, fatigue testing, fracture surface morphology*

Application of traditional materials and development of new ones requires knowledge of the change of physical and structural characteristics under the conditions of cyclic loading, as they reflect the level of material resistance to macrocrack development in a specified structural state and operation modes. Loading periodicity increases localization of plastic deformation in a material, changes its stressed state and causes restructuring in microvolumes, which is a response to external impact [1–6]. Exhaustion of material capability for further plastic deformation leads to its fracture.

In welded joints structural zones are singled out, in which complex multiphase structures form under the impact of the thermal cycle of welding. Differences between heterogeneous base metal grains and weld crystallites formed in welding cause the appearance of stress concentration gradient in the welded joint. An increase of the width of intergranular space in the heat zone is accompanied by an increase of the number of eutectic phases forming as a result of development of chemical inhomogeneity by the main alloying elements and impurities, because of their segregation along the grain boundaries [2]. This results in a change of the dimensions, shape and configuration of the location of phase precipitates, coagulation of intermetallic phase inclusions, leading to formation of coarser structure regions in the joint zone, that influences the localization of plastic deformations in the HAZ metal, leading to realization of different fracture micromechanisms, accompanying the processes of crack initiation and propagation [3].

The purpose of this work is establishment by the method of fractographic analysis of morphological and structural features of microrelief on fatigue fracture surface of welded joints of high-strength AMg6 aluminium alloy 12 mm thick, made by consumable electrode. Welding of samples was performed in a mixture of argon and helium (50 + 50 %) by a pulsed arc in the following mode: $I_w = 220$ A, $U_a = 23$ V, $v_w = 30$ m/h using TPS-450 power source (Fronius, Austria). Samples of welded joints across the weld with technological reinforcement and without it were cut out of butt joints.

After welding some joints of the alloy were subjected to mechanical peening in the narrow zone of weld to base metal transition by applying a single-row group of steel strikers of 5 mm diameter, brought into directed motion by a small-sized portable ultrasonic generator (of 0.3 kW power) and manual tool with piezoceramic converter of ultrasonic oscillations into mechanical oscillations [7]. The speed of striker displacement along the weld was equal to 5 mm/s.

Fatigue testing was conducted under the conditions of alternating load along sample axis with 5–6 Hz frequency by a standard procedure in MTS-318.25 machine with maximum axial load of 25 t. Error of measurement of the applied force did not exceed 1 %.

Condition of the metal after welding and performance of high-frequency mechanical peening of the surface of the zone of weld fusion with the base metal was studied by fractographic analysis. Change of the shape and dimensions of individual fragments of the relief of welded joint fracture was examined in the scanning electron microscope JSM-840 with a system of Link-860/500 microanalyzer (at accelerating voltage of 15, 25 and 30 kV).

Visual analysis of fracture surface of samples of AMg6 alloy welded joints after testing at cyclic load with coefficient of asymmetry $R_\sigma = 0$ showed that the fatigue crack initiates on the boundary of weld fusion with the base metal and propagates in the HAZ direction with further transition into the base metal, forming the main crack (Figure 1). Fracture contains three characteristic relief zones: purely fatigue fracture, fatigue fracture with a rough surface as a result of plastic deformation, final fracture zone, which was formed by tough fracture mechanism. Presence of dif-

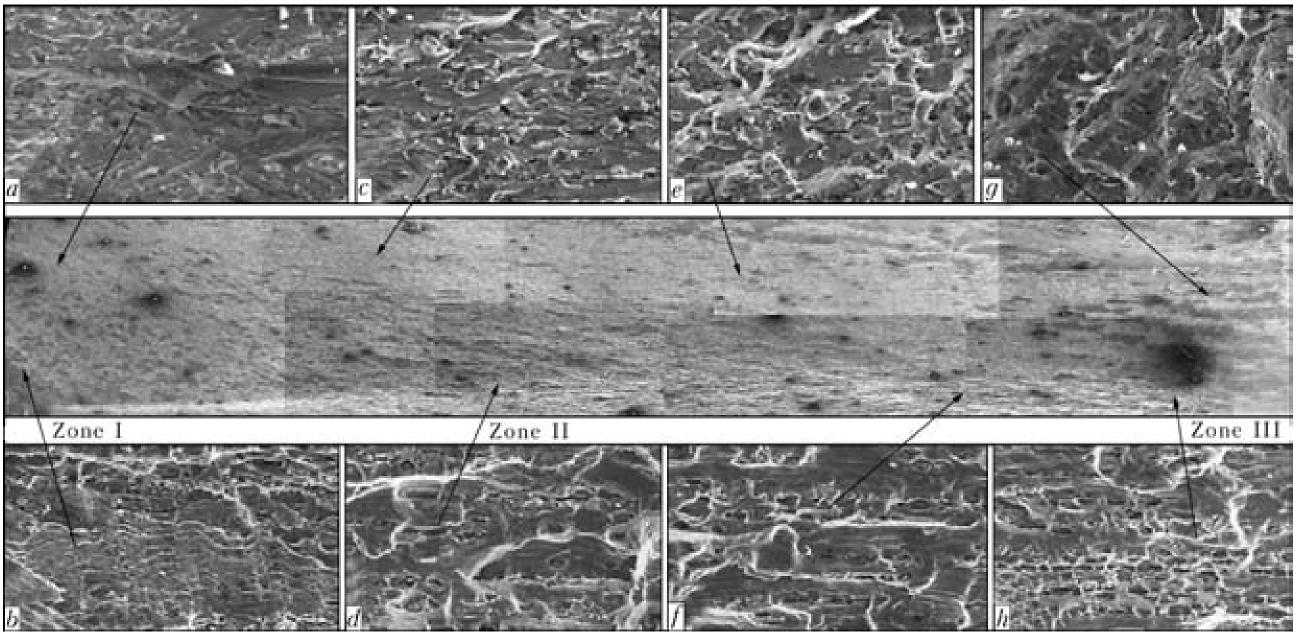

Figure 1. Fracture panorama (×13) and fractographs of its individual fragments (×500) in MIG-welded joints of AMg6 alloy tested at cyclic loading with coefficient of asymmetry $R_\sigma = 0$ (for *a*–*h* see the text)

ferent topography of the relief regions on fractures of the studied samples points to different degrees of plastic deformation, which accompanies the processes of initiation and propagation of the main fatigue crack during testing. The colouring of fracture regions, where the fatigue crack initiates and propagates, is bright, and the final fracture zone is of mat colour. Its relief has several deep cracks, which run in-depth of the sample and are oriented along the axis of application of cyclic load. Their extent on the fracture surface is equal to 10–50 μm, which is attributable to insufficient quality of the alloy working during manufacturing of the semi-finished product.

Topography of the region, where the site of fatigue crack initiation formed, is due to the characteristic features of the structure of weld metal on AMg6 alloy and conditions of cyclic testing (Figure 1, *a*–*h*). Level of local microstresses, which remained on the boundary of weld metal crystallites after phase transformation during the welding cycle, affects the process of microcrack initiation. Change of activation energy in the metal and concentration of plastic shears in individual, most stressed weld crystallites at achievement of the critical value of stress range, is accompanied by their localization, formation of slip bands, shifting of one part of the crystal relative to another along crystallographic surfaces of the same orientation [4, 5]. This not only causes appearance of the fatigue crack source, but also determines the nature of its further propagation.

In the fracture plane the crack is a flat surface in the form of a fan, propagating in the radial direction relative to the oxide film located in the weld near the fusion zone. This is indicative of the fact that the film is the site of fatigue crack initiation. Flat regions of intergranular fracture are present on the fracture surface. Indications of brittle crack initiation with kink steps (Figure 1, *b*) are also observed, which are manifested when the crack tip runs into screw dislocations crossing the cleavage plane [4, 6]. These may be dislocations, present in the alloy, or generated by the fatigue crack tip. Traces of the action of tough micromechanism, which is realized as a result of plastic deformation localization under the conditions of an alternating loading, are insufficient. A considerable number of deformed weld crystallites on the fracture surface of the studied sample in as-welded condition, is indicative of the fact that slip bands are intensively developing during crack propagation.

During the period of stable growth the main crack propagates in an intercrystalline mode along the boundaries of grains, which are fringed with intermetallic phases. Their coagulation during welding heating, as well as increase of the width of the intercrystalline space, volume of eutectic phases formed as a result of segregation of alloying elements and impurities, cause metal softening in the near-boundary regions and intensive initiation of microcracks by the cleavage mechanism. Morphological relief elements that are formed in this case, can be compared by their size with the matrix (solid solution), regions of intermetallic phase location, and facet structure elements. The width of longitudinal microcracks does not change as they propagate, remaining equal to 1.5–2.0 μm. Crack length is increased through coalescence of individual microcracks, and its path acquires a zigzag shape (Figure 1, *c*, *d*).

Located beyond the fatigue crack is the zone of action of mixed fracture mechanism, in which alongside flat sections of the relief, indications of plastic deformation realization at propagation of the main crack by the tearing mechanism are also observed (Figure 2). Transition to the zone of mixed fracture occurs as a result of increase of the number of deformed grains. Branching of microcracks observed in the fracture indicates that location of coarse phase particles on the crystallite boundary prevents the translational motion of the main crack. This leads to its deceleration, increase of additional local deformation in the metal microvolume and, consequently, to a change of its propagation direction. All these processes are accompanied not only by a change of relief structure near the crack, but also development of fatigue striation, similar to facet structure bands (see Figure 1, *e*, *f*), manifestation of which is related to increase of dislocation density [8]. There are also relief regions, where the crack propagates through the crystallite that is in a transcrystalline mode. Relief protrusion of fatigue striations indicates the direction and nature of propagation of the main crack.

Specific marks, which are called «track traces» can be also seen on the surface of this fracture region (Figure 2, *a*). They are considered to be indications of fatigue fractures, forming at failure of aluminium and its alloys [8]. The marks are characterized by an exceptionally clear-cut pattern, and are found only in the smooth portions of the relief. They form paths between them, coinciding with the direction of the main crack propagation. Quantity of marks in different fracture sections does not coincide, and the distance between them decreases with increase of the row length (Figure 2, *b*). Publications do not provide an accurate substantiation of the causes for «track traces» appearance in the relief of fatigue fractures. They are associated with manifestation of the secondary effect of the influence of inclusions, phase precipitates or solid insoluble structural components, which protrude above the crack surface during its displacement, as well as the result of interaction of local tangential and normal alternating stresses [9–11].

Presence of a considerable quantity of pits of a parabolic shape, forming in case of shear mechanism of fracture, should be regarded as one of the features of relief structure of final fracture zone (see Figure 1, *f*–*h*). They form from micropores as a result of development of plastic deformation and plastic decohesion under the conditions of cyclic loading [9]. Such processes usually run along the boundaries between the inclusions and matrix in those cases, when the forces of adhesion between them are insufficient, and cause an increase of local stress concentration leading to initiation of microcracks. This is indicated by presence of fragments of broken inclusions or phase precipitates on the pit bottom. Microcracks were observed along grain boundaries. Change of pit orientation and increase of the number of microcracks in the relief of final fracture region, compared to the total panorama of fracture of the studied sample, are indicative of the difference in the local conditions of plastic deformation at the stage of completion of the fracture process.

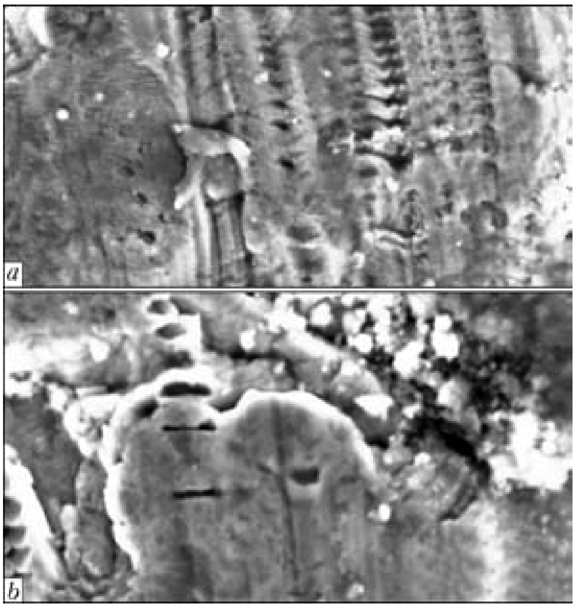

Figure 2. Fracture fractograms (×1000) with characteristic patterns of specific «track traces» marks (for *a*, *b* see the text)

Generalizing the obtained information, the following characteristic features of structure morphology in the fracture of AMg6 alloy welded joint can be noted: fatigue crack initiation site is located on the surface near the zone of weld fusion with the base metal; oxide film is the initiator of fatigue crack; presence of three relief zones in the fracture is indicative of a mixed and multi-site nature of fracture of samples under the conditions of cyclic loading.

Change of the coefficient of asymmetry at cyclic testing from $R_\sigma = 0$ up to more complicated conditions ($R_\sigma = -1$) causes an intensification of plastic deformation localization, and, consequently, change of the nature of fracture relief in the studied samples of welded joints (Figure 3). Fatigue crack initiates beyond the weld in the HAZ metal and propagates in the direction of the base metal, forming the main crack. Its propagation is the result of coalescence of individual microcracks, developing along the slip steps or at crossing of slip planes of two systems. Main crack develops in the intercrystalline mode along grain boundaries, causing brittle intercrystalline fracture with traces of small plastic deformations. Such fractures form under the conditions of lowering of cohesion forces between the structural components located on the boundaries between the grains. Their level in this case should be lower than cohesion in the cleavage plane or slip plane [1–4]. The greatest degree of lowering of adhesion between the grains is noted in samples at cyclic testing with the coefficient of asymmetry $R_\sigma = -1$, which is indicated by three times reduction of the number of cycles to fracture (490,120 cycles). The above phenomenon may be the consequence of brittle nature of intermetallic phases or presence of residual stress as a result of segregation of alloying elements and impurities under the conditions of welding.

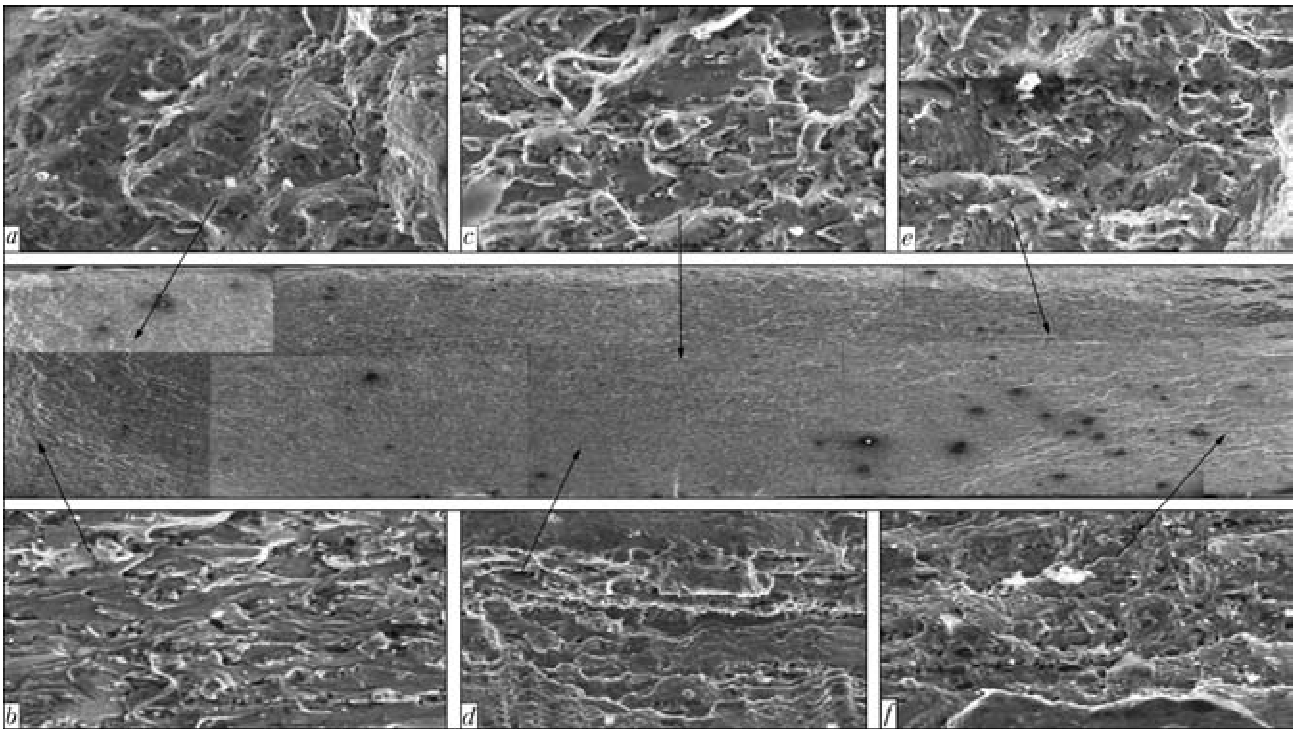

Figure 3. Fracture panorama (×13) and fractographs of its individual fragments (×500) in MIG-welded joints of AMg6 alloy tested at cyclic loading with coefficient of asymmetry R_σ = 0.4 (for *a*–*f* see the text)

Increase of loading frequency at R_σ = 0.4 is accompanied by increase of the degree of striation disorientation relative to the direction of microcrack movement and appearance of fine secondary striation, slip traces, and steps (Figure 3, *a*–*c*). A decrease of fatigue striation step and increase of the number of secondary microcracks is noted, the microcracks initiating on the fatigue striation and propagating normal to the fracture surface in-depth of the material. The non-simultaneous nature of realisation of the movement of individual microcracks at testing causes coalescence of the steps and leads to a change of the mechanism of fatigue crack propagation from the brittle to the mixed type (Figure 3, *d*–*f*). Here the number of ductile bridges in the fracture increases, and plastic shear fragments appear at formation of facet ridges.

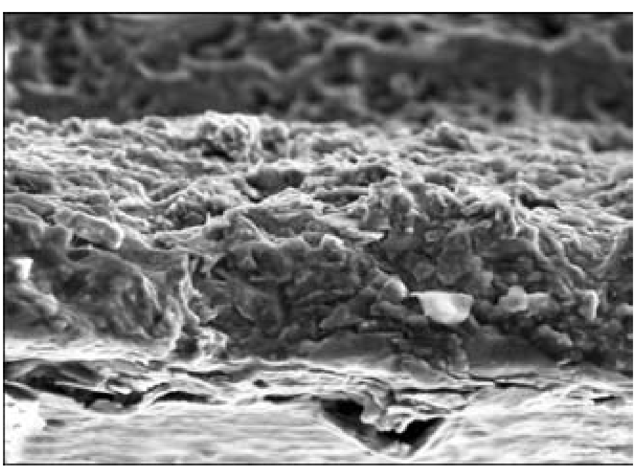

Figure 4. Fragment of the surface (×500) of fracture of AMg6 alloy welded joints near the surface of the zone of transition from the weld to base metal after fatigue testing at R_σ = −1

All together this enhances the diversity of relief morphology across the width and along the length of fatigue striation and facet structure bands. Physical basis of such a process is increase of the level of local plastic deformation of metal as a result of structural change, for instance, cleavage crack crossing the grain body or fracture (delamination) of blocks of one crystallographic order [1–3].

The relief of final fracture zone in such a sample contains a large number of pits of a parabolic shape formed as a result of the processes of tear and shear (see Figure 3). Here increase of the level of local plastic deformation in the microvolume changes the pit shape and direction of orientation, and increases the number of microcracks compared to the general pattern of final fracture zone relief. The site of initiation of primary microcracks are matrix boundaries with insoluble intermetallic inclusions or phase precipitates that points to a lowering of decohesion forces between them under the conditions of welding heating as a result of segregation of alloying elements and impurities. Research results are in good agreement with the data of [1–5]. It is noted in them that the high loading frequency as cyclic testing with the coefficient of asymmetry R_σ = 0.4 causes a fast change of the stressed state in the metal and leads both to formation of a striated relief on the fractures, and to cleavage fracture through the structural components and interphases, thus promoting appearance of secondary fatigue cracks.

High-frequency peening of the surface in the narrow zone of weld fusion with the base metal of AMg6 alloy ensures formation of a smooth geometry of weld

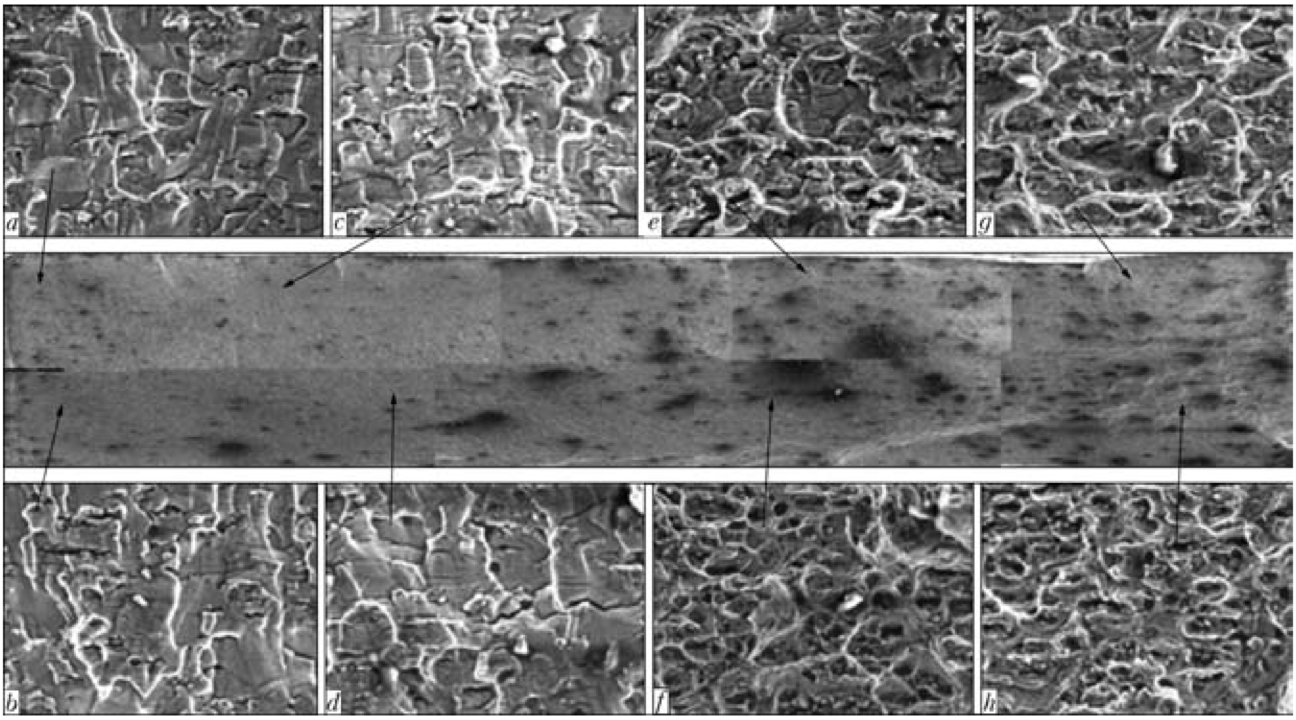

Figure 5. Fracture panorama (×13) and fractographs of its individual fragments (×500) in MIG-welded joints of AMg6 alloy treated by peening and tested at cyclic loading with coefficient of asymmetry $R_\sigma = -1$ (for *a–h* see the text)

to base metal transition and lowering of average values of the stress concentration factor. Positive effect of peening is manifested also in formation of a favourable structure, ensuring an increase of microplastic deformation resistance of the surface layer and formation of high residual compressive stresses [12]. As shown by fractographic investigations of the fracture surface of welded joint samples after cyclic testing in the low-cycle region with the coefficient of asymmetry $R_\sigma = 0.4$, effect of metal strengthening from performance of peening is small (Figure 4). Number of cycles to fracture is equal to 17000. Quasi-cleavage regions containing individual microcracks against the background of fine and small pits are located in the subsurface layer of the fusion zone on the fracture along the grain boundaries. In addition, development of an

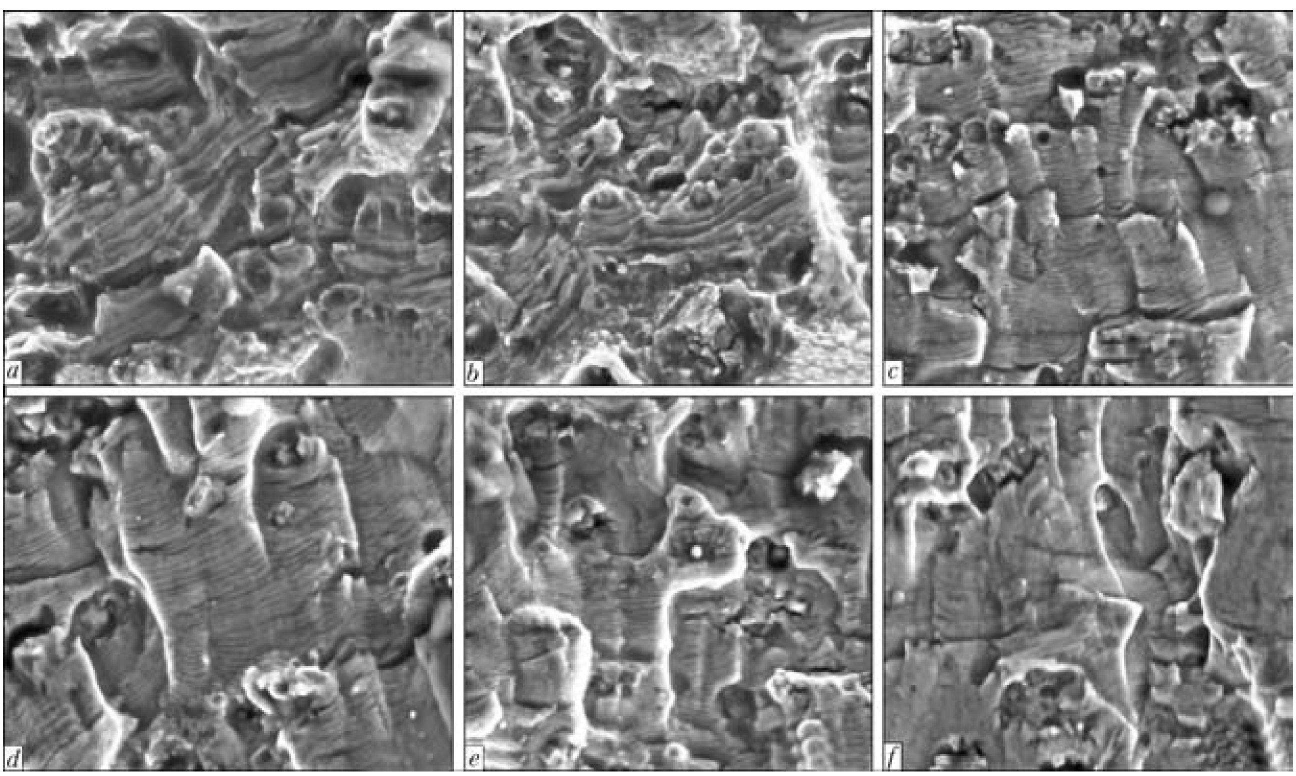

Figure 6. Examples of sections (×1000) of an abrupt transition from the tough mode of striation formation to their brittle delaminations (for *a–f* see the text)

abrupt transition from tough striation to brittle delamination is possible in the subsurface layers (Figure 5). At ×1000 magnification of the relief details one can see that the line which separates the striation from the other structural components, is a crack (Figure 6, *c*–*e*). It forms as a result of simultaneous delamination of metal along several crystallographic planes that may be due to lowering of their strength under the impact of deformation inducing compressive stresses. It should be noted that delamination is not a site of fatigue crack initiation. Therefore, the layer strengthened by peening, is involved into the process of fatigue fracture, and its site is shifted under the deformed layer. Crack propagation proceeds in the fracture section, characterized by a lower fracture resistance.

CONCLUSIONS

1. An intercrystalline mechanism of fatigue crack propagation at cyclic testing with loading cycle asymmetry $R_\sigma = 0$ of MIG-welded joints of AMg6 alloy was established. Presence of three relief zones on fracture surface is indicative of the fact that welded joint fracture on the microlevel is of a mixed and multi-site nature. Localization of plastic deformation in the welded joint and, consequently, crack initiation occur as a result of a change of the dimensions, shape and pattern of phase precipitation location, as well as coagulation of intermetallic phase inclusions occurring at welding heating, thus lowering the total resistance of the metal to fatigue crack propagation.

2. Change of the coefficient of asymmetry at cyclic testing from $R_\sigma = 0$ to more complex conditions ($R_\sigma = -1$) leads to intensification of plastic deformation localization, shortening of fatigue striation step and increase of the number of secondary microcracks, which initiate at fatigue striation and propagate normal to fracture surface in-depth of the metal. At the stage of crack propagation, fatigue striation is characterized by periodicity of the step with a small change of orientation at transition from crystallite to crystallite.

3. High-frequency peening in a narrow zone of the surface of transition of AMg6 alloy weld to base metal using steel strikers ensures formation of a smoother geometry of the zone of weld transition to base metal and lowering of average values of the of stress concentration factor. The strengthened layer relief shows quasi-cleavage regions, which contain individual microcracks along grain boundaries against the background of fine and small pits. In the subsurface layers of the fusion zone a large number of flat sections and microcracks can form, as well as an abrupt transition from tough striation to brittle delamination. The fatigue crack propagates under the peened metal layer.

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