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STRENGTH AND STRUCTURE OF BUTT, OVERLAP AND FILLET JOINTS OF AMg6M ALLOY PRODUCED BY FRICTION STIR WELDING

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ABSTRACT

The paper deals with the results of studying the structure and strength of butt, overlap and fillet joints of AMg6M aluminium alloy, produced by friction stir welding (FSW). It is shown that a weld nugget with fine-crystalline structure forms as a result of intensive plastic deformation of the metal. The size of grains, which are of practically globular shape, does not exceed 4–5 μm, and that of dispersed phase precipitates — ≤ 1 μm. In the zone of thermomechanical impact, in addition to fine grains, somewhat larger elongated grains (6–7 мкм) form on the boundary of the weld-to-base metal transition, which are oriented along the direction of plasticized metal displacement by the tool working surfaces. Here, in the HAZ, where the metal did not undergo any deformational impact, the maximum size of its grains is on the level of 10–15 μm. The ultimate strength of samples of butt joints and fillet joints, produced by making butt and overlap-butt welds, is on the level of 335–350 MPa at their static tension, and it practically does not depend on the welded sheet location either from the advancing side or from the retreating side, or on the weld orientation relative to their flanging direction. Here, the butt joint samples fail mainly through the base metal or the boundary of thermomechanical impact zone and heat-affected zone. Samples of fillet joints produced by overlap-butt welds, fail in the zone of weld-to-base metal transition in the thermomechanical impact zone, and those produced by butt welds fail also through the base metal.

KEYWORDS: friction stir welding, AMg6M aluminium alloy, fillet joints, strength, structure, butt joints, overlap joints

INTRODUCTION

The scope of aluminium application in different industries is growing constantly owing to its physical, mechanical and technological properties. The main sectors, which determine the global demand for aluminium alloys, now are construction, packing, general engineering, aerospace engineering, car making and power engineering. Aluminium rolled stock and shaped sections are widely used in industrial and civil construction, in particular for fabrication of lightweight welded structures. Aluminium application in car-making allows a significant increase of strength at reduction of the weight and preservation of the dimensions of cars, ensuring fuel saving. In the aerospace sector aluminium has long been the main structural material and makes up almost 80 % of the aircraft fuselage weight. The modern global aluminium market offers to consumers pure aluminium and almost 300 compositions of structural aluminium alloys with different physico-mechanical properties. The range of marketable products from aluminium and its alloys includes cast ingots, flat rolled stock, shaped sections, extrusions, wire and foil. Therefore, at fabrication of welded structures, depending on their functional purpose, both different aluminium alloys and diverse kinds of semi-finished products are usually used [1].

Increase of the scope of aluminium application is inseparably connected not only with development of new readily weldable alloys, but also with improvement of the currently available and development of promising welding technologies, which allow expansion of their application areas. So, intensification of stirring of molten metal of the weld pool in nonconsumable electrode argon-arc welding with arc oscillation promoted reduction of porosity in welds of aluminium-lithium alloys, breaking up and fragmentation of macroinclusions of oxide film in welds of aluminium-magnesium alloys and formation of a fine-crystalline crack-resistant weld structure [2, 3]. Application of highly-concentrated heat sources in beam and hybrid welding processes enabled reduction of the degree of metal softening in the zone of permanent joint formation and improvement of mechanical properties of welds [4]. Development of FSW process allowed producing welds without application of shielding inert gas or welding wire, avoiding ultraviolet arc radiation and the processes of metal melting and solidification, which lead to formation of defects characteristic for fusion welding in the form of hot cracks, pores and oxide film macroinclusions [5–7]. During FSW, favourable conditions are in place for formation of fine-crystalline weld structure, as a result of plastic deformation of metal [8–10]. Owing to formation of permanent joints at much lower temperatures ($\leq T_S$) compared to fusion welding, the degree of metal softening decreases, high level of the joint mechanical properties and low level of residual stresses and strains is ensured [11–13]. The advantages of FSW process promoted its wide acceptance by industry at manufacture of undetachable components and structures in different sectors. In shipbuilding it is applied to produce large-sized panels from separate extruded profiles, which are used at fabrication of side sections of the hulls of ships, ferries, launches and boats, walls of refrigerators and cabins, deck superstructures, platforms for helicopters, gangways, masts, oil platforms, etc. In manufacture of railway transport, this process is used to join profiles and rigid integrated panels from different aluminium alloys. In the automotive industry FSW is successfully used in manufacture of the car boot and doors, space frames of motorcycles and bicycles, bodies and lifting devices of trucks, bodies and floors of buses, vans, trailers, elements of chassis, wheel rims, etc. In construction it is used to weld panels of walls and facades, window and door frames, floors and other building elements. This process has become important in construction of bridges, allowing their weight to be reduced and mounting operation duration to be shortened. In the aerospace sector, FSW is used for manufacture of elements of aircraft and missile fuel tanks. In most cases, when designing various components of such products, butt welded joints are predominantly used. It, however, cannot always be done, so that overlap, fillet or tee joints have to be used [14–16].

The objective of this work is investigation of the structure and assessment of the strength of butt, overlap and fillet joints of sheets from AMg6M alloy, produced by FSW.

INVESTIGATION PROCEDURE

Sheets of batch-produced AMg6M aluminium alloy (400×200×1.9 mm) were used to produce butt and overlap joints. Here, four variants of butt joints were welded, depending on weld orientation relative to sheet flanging direction, located from the advancing side (where the directions of rotation and linear displacement of the tool coincide) and the retreating side (where the directions are opposite). The first variant is when both the sheets were positioned along the flanging direction (D), and the second one is when both the sheets were positioned across the flanging direction (P). In the third and fourth variants the sheet oriented along the flanging direction was placed from the advancing side, and the sheet across the flanging direction was located from the retreating side, and vice versa.

Depending on weld position relative to the direction of flanging of the upper and lower sheets, four variants of overlap joints were also produced. In the first and second variant the upper and lower sheets were placed along or across their flanging direction relative to weld orientation, and in the third and fourth variants the upper and lower sheets had different directions of flanging relative to weld orientation.

Fillet joints were produced by making butt and overlap-butt welds, welding similar sheets to 12.0 mm sheets. In the second case, a recess of 6 mm width (half the shoulder diameter) and 1.9 mm depth (thinner sheet thickness) was made in the thick sheet. Here, thicker sheets were placed from the advancing side or from the retreating side.

In keeping with the requirements to welded joints of critical structures, standard chemical etching of the sheets was carried out in NaOH solution with subsequent clarification in HNO_3 solution, and directly before welding mechanical scraping of the sheet surface was performed in the weld formation zone.

FSW was conducted in a laboratory set-up developed at PWI with welding speed V_w = 10 m/h at tool rotation frequency N = 1420 rpm, using a special tool with shoulder diameter of 12 mm and pin in the form of a truncated cone of 3.4 mm diameter at the shoulder base and 12° inclination angle of the forming cone [37]. When welding butt and fillet joints by butt welds, the pin length was 1.75 mm and in welding overlap and fillet joints by overlap-butt welds it was 2.25 mm, so as to ensure a reliable connection of the upper sheet with the lower one.

The produced welded joints were used to cut out sections to study their structural features. The ultimate strength of butt and fillet joints was determined at static uniaxial stretching of standard flat samples with 15 mm width of the working part in versatile servohydraulic system MTS 318.25. The structural features of welded joints were evaluated using an optical electron microscope MMT-1600V.

RESULTS AND DISCUSSION

The conducted experimental studies revealed that at FSW of butt and overlap joints, irrespective of weld orientation relative to the sheet flanging direction, the nature of formation, appearance and macrostructure of such joints remain the same (Figures 1, 2). Thus, at FSW the metallurgical heredity does not affect the structure of such sheet joints of AMg6M aluminium alloy.

Microstructural studies showed that the weld nugget with a fine-crystalline structure forms in the central part of welds in butt joints, as a result of intensive plastic deformation. The size of grains, having a practically globular shape, is not more than 4–5 μm, and that of dispersed phase precipitates is ≤ 1 μm. In the thermomechanical impact zone partial deformation of the metal takes place at the boundary of weld-to-base material transition, so that in addition to fine grains, somewhat larger (6–7 μm) elongated grains

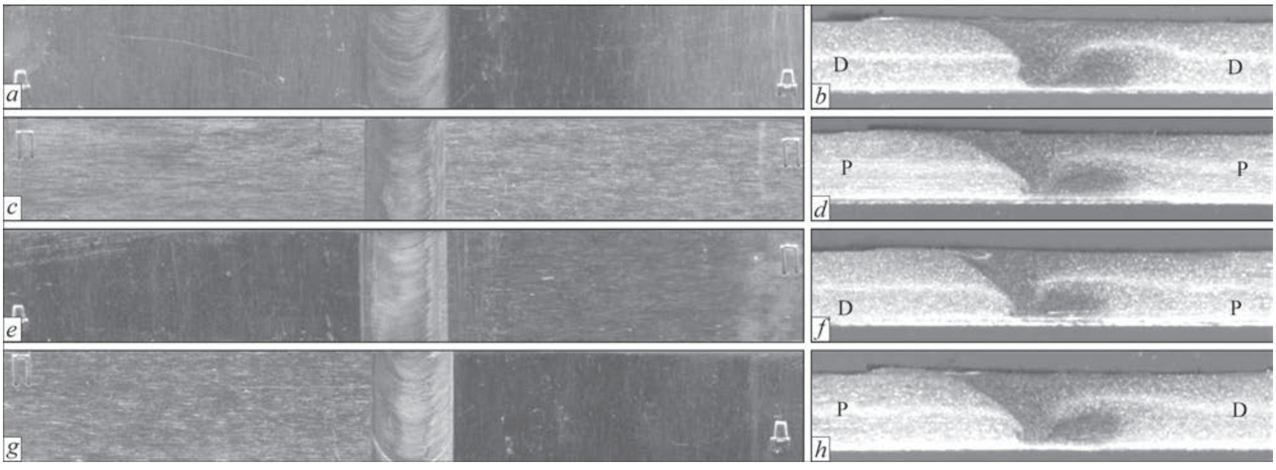

Figure 1. Appearance of surfaces (*a*, *c*, *e*, *g*) and cross-sections (*b*, *d*, *f*, *h*) of butt joints of 1.9 mm AMg6M aluminium alloy, produced by FSW at different orientation of welds relative to the sheet flanging direction (sheet position): D — along the flanging direction, P — across the flanging direction)

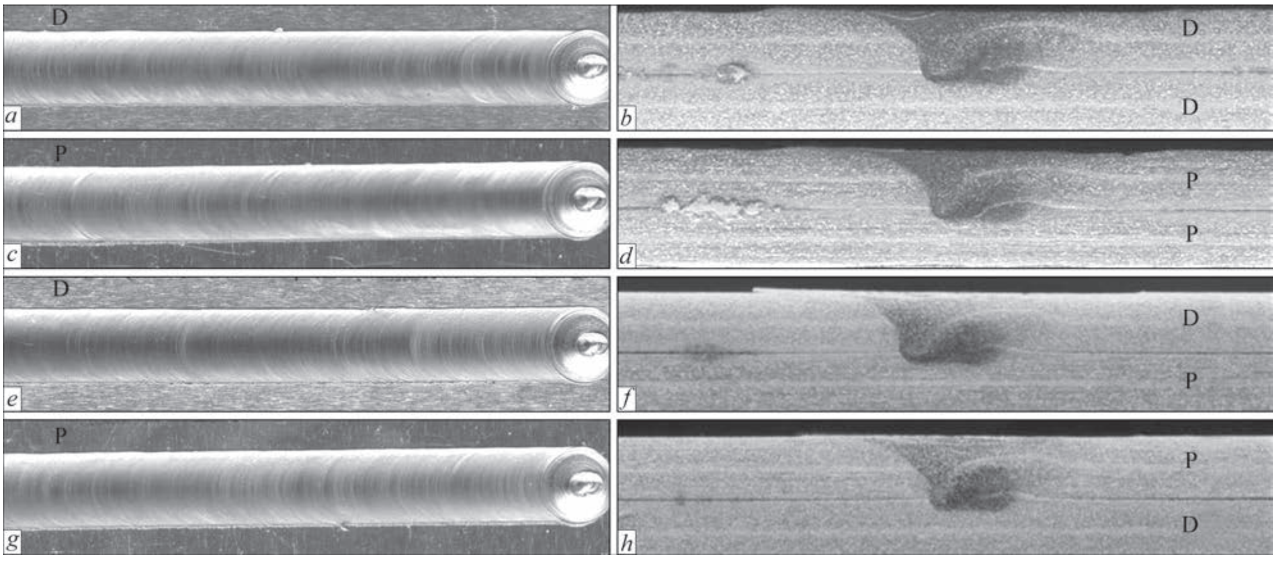

Figure 2. Appearance of surfaces (*a*, *c*, *e*, *g*) and cross-sections (*b*, *d*, *f*, *h*) of overlap joints of 1.9 mm AMg6M aluminium alloy, produced by FSW at different weld orientation relative to sheet flanging direction (sheet position): D — along the flanging direction; P — across the flanging direction)

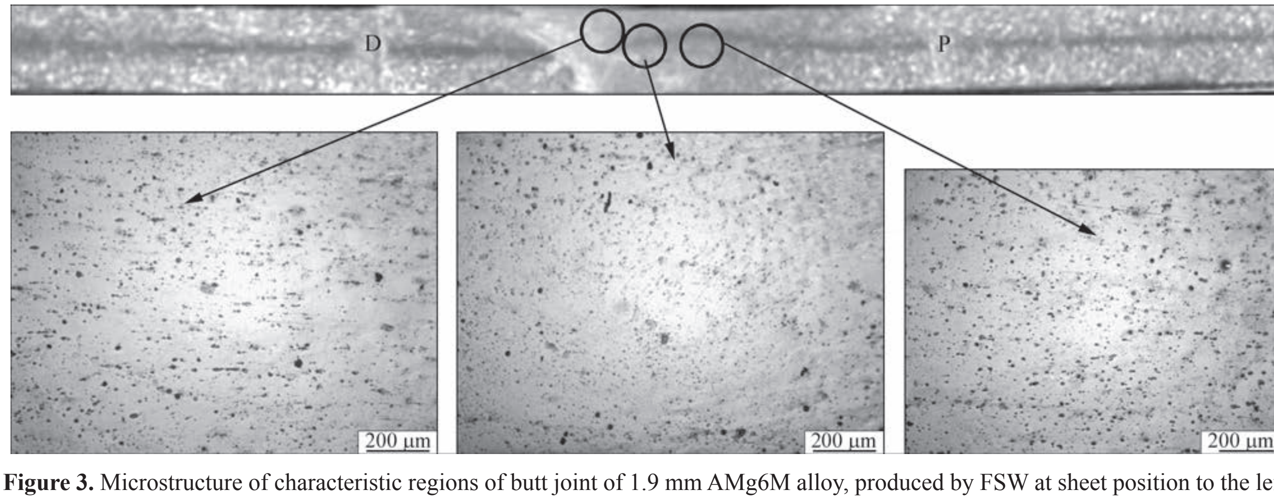

Figure 3. Microstructure of characteristic regions of butt joint of 1.9 mm AMg6M alloy, produced by FSW at sheet position to the left (from the advancing side) along its flanging direction, and to the right (from the retreating side) — across its flanging direction (sheet position: D — along the flanging direction, P — across the flanging direction)

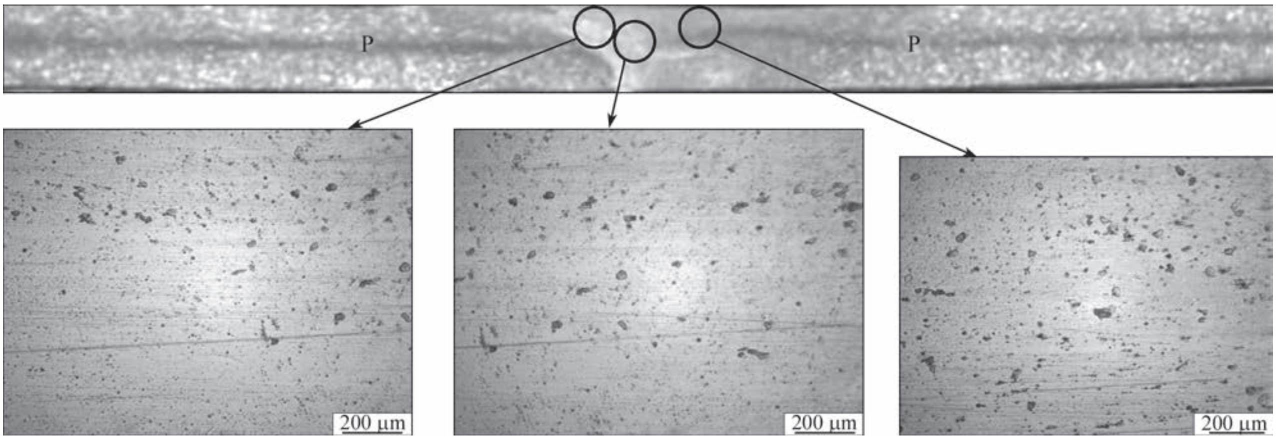

Figure 4. Microstructure of characteristic regions of butt joint of 1.9 mm AMg6M alloy, produced by FSW at both sheets positioned across their flanging direction (sheet position: D — along the flanging direction, P — across the flanging direction)

form, which are oriented along the direction of plasticized metal displacement by the tool working surfaces. Owing to weld formation in the solid phase at FSW, unlike fusion welding, there are no conditions for formation of one of the defects, characteristic for aluminium alloy welded joints, namely concentration of low-melting eutectic inclusions on the weld boundary with the base material (Figures 3, 4). Analysis of overlap joint microstructure also showed formation of a new fine-grained microstructure in the weld nugget, which is independent of the features of the metal initial structure, from which it formed. Now, in the zones of weld transition to base material grain deformation takes place, as a result of thermomechanical impact (Figures 5, 6).

Figures 7, 8 shows the microstructure of the characteristic regions of welded joints, produced at FSW of fillet joints by making butt and overlap-butt welds. Analysis of the microstructure of fillet joints produced by butt welds, showed that similar to welding of sheet butt joints, a weld nugget with a fine-crystalline structure forms in the weld central part, as a result of intensive plastic deformation of metal. The size of grains, having a practically globular shape, is not higher than 4–5 μm, and that of dispersed phase inclusions is ≤ 1 μm. In the thermomechanical impact zone on the boundary of weld-to-base material transition, both from the side of the thin (1.9 mm) and from the side of the thick (12.0 mm) sheets, in addition to fine grains, somewhat larger (6–7 μm) elongated grains form, which are oriented along the direction of displacement of plasticized metal by the tool working surfaces. Here, in the HAZ, where the metal was not exposed to deformational impact, the maximum size of its grains is on the level of 10–15 μm. In welding of fillet joints by overlap-butt welds no essential differences in the microstructure of its characteristic subzones is observed (see Figure 8).

For the studied AMg6M alloy the ultimate strength of base metal for samples cut out along the sheet flanging direction, is on the level of 370 MPa, and for those cut out across this direction, it is on the lev-

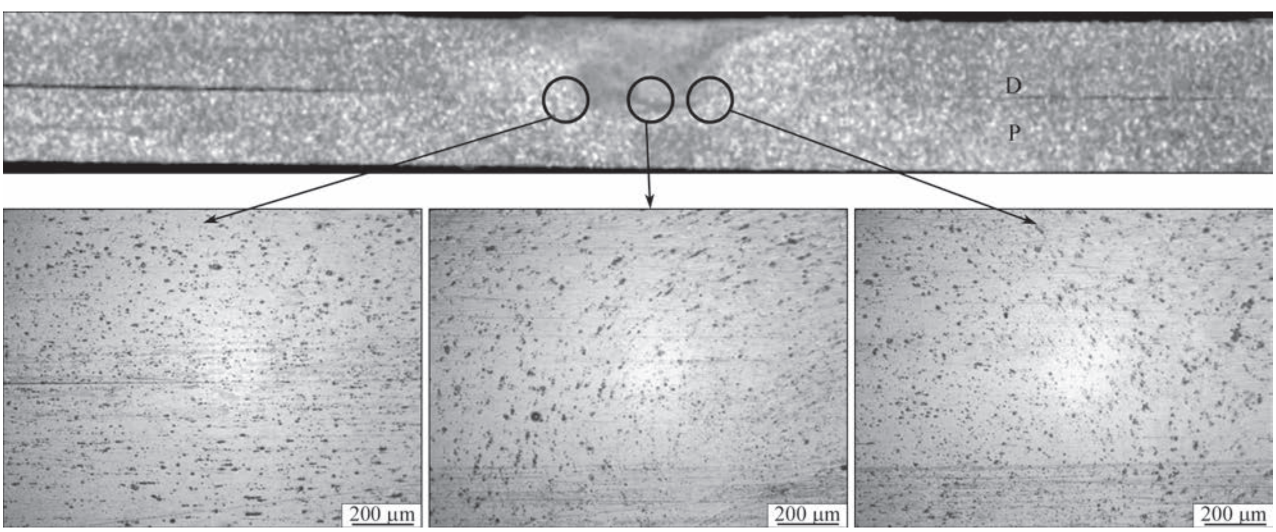

Figure 5. Microstructure of characteristic regions of overlap joint of 1.9 mm AMg6M alloy, produced by FSW at weld orientation along their flanging direction on the upper sheet, and across their flanging direction on the lower sheet (sheet position: D — along the flanging direction, P — across the flanging direction)

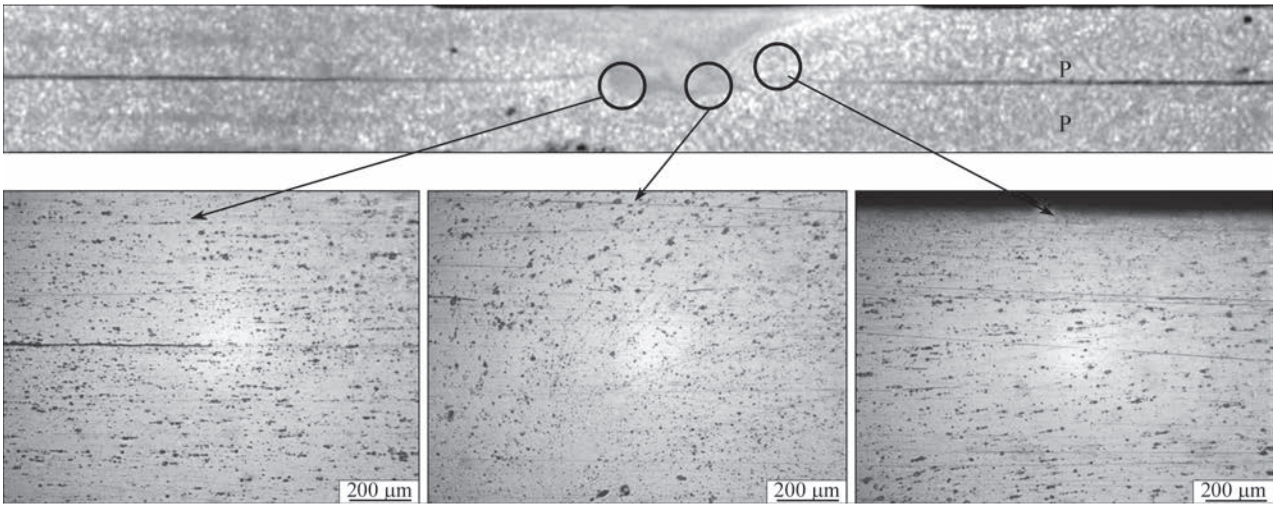

Figure 6. Microstructure of characteristic regions of overlap joint of 1.9 mm AMg6M alloy, produced by FSW at weld orientation across sheet flanging direction on the upper and lower sheets (sheet position: D — along the flanging direction, P — across the flanging direction)

el of 359 MPa. As a result of the conducted studies it was found that the ultimate strength of samples of butt joints, in which the sheet flanging direction is normal relative to the weld orientation, both from the advancing and from the retreating side, is on the level of 343–350 MPa. At static tension of such samples they fail through the base material from the advancing or the retreating side, or on the boundary of the thermomechanical impact zone and the heat-affected zone from the retreating side (Figure 9, *a*–*c*).

When testing samples of butt joints, where sheet flanging direction is normal from the advancing side,

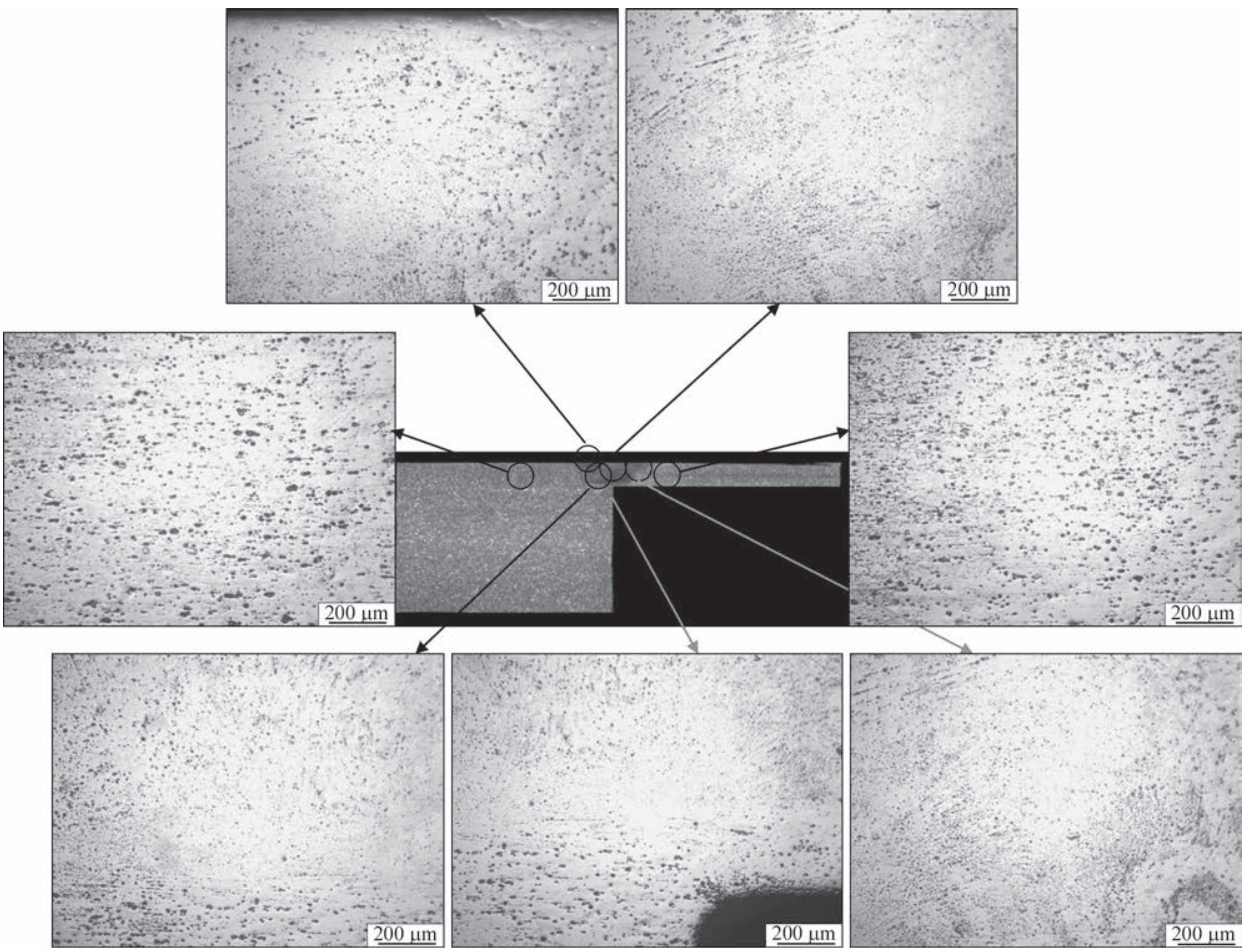

Figure 7. Microstructure of characteristic regions of fillet joint of 1.9 mm AMg6M alloy, produced by FSW by a butt weld with 12.0 mm sheet placed from the advancing side

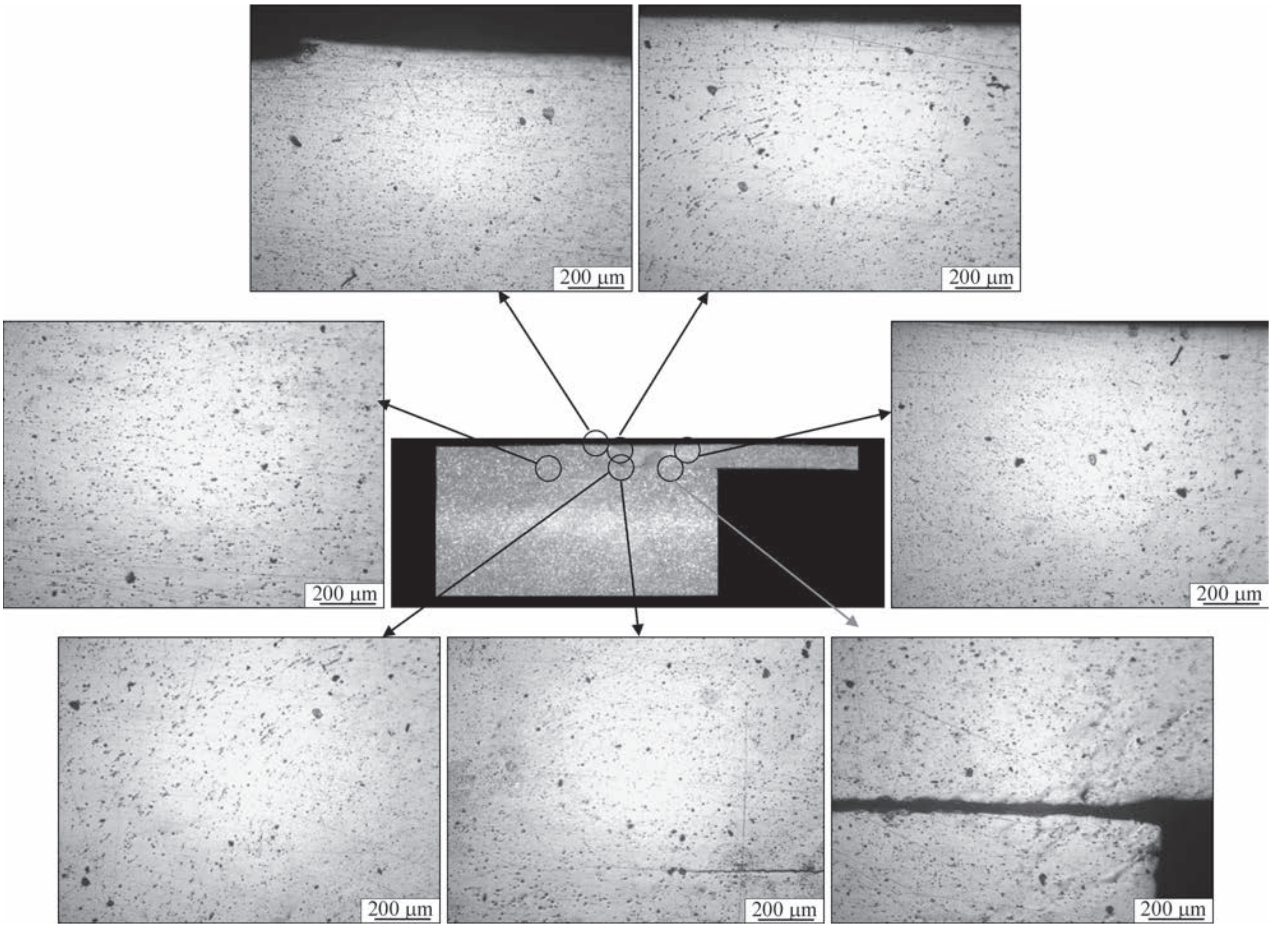

Figure 8. Microstructure of characteristic regions of fillet joint of 1.9 mm AMg6M alloy, produced by FSW by an overlap-butt weld with 12.0 mm sheet placed from the advancing side

and parallel relative to weld orientation from the retreating side, the ultimate strength is somewhat lower and it is on the level of 336–343 MPa. This is due to the fact that the samples fail through the base metal or on the boundary of the thermomechanical impact zone and the heat-affected zone from the retreating side, where the forces at their stretching are directed normal to the sheet flanging direction, and the base

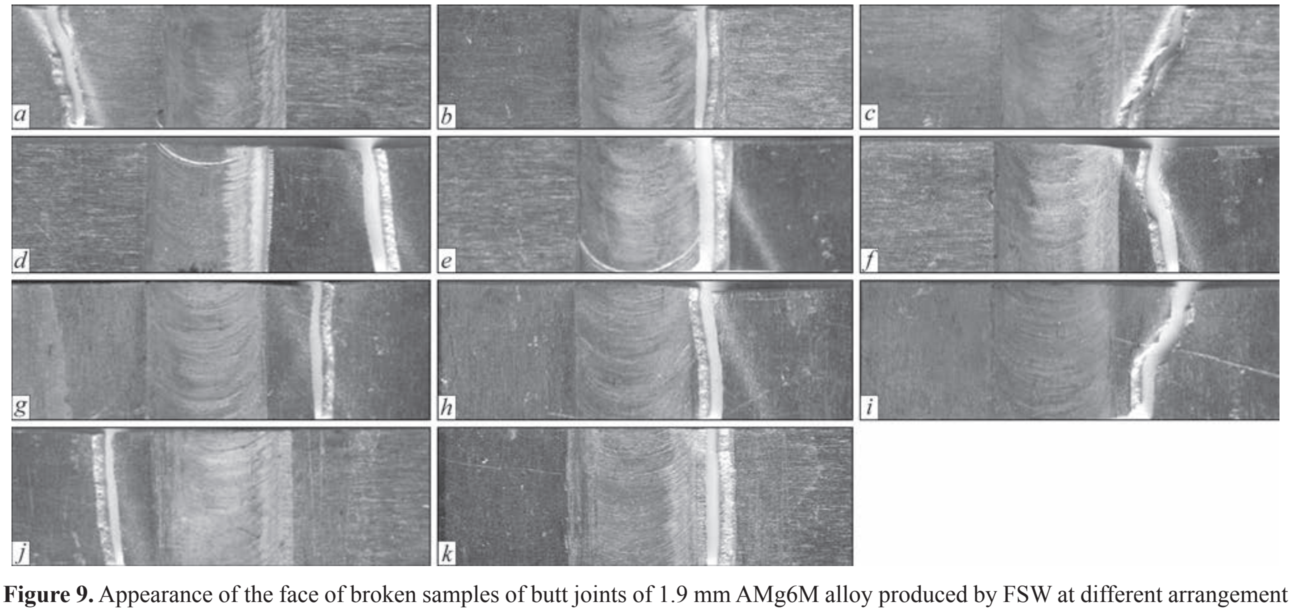

Figure 9. Appearance of the face of broken samples of butt joints of 1.9 mm AMg6M alloy produced by FSW at different arrangement of sheets relative to weld orientation: *a–c* — from the advancing side and from the retreating side their flanging direction is normal relative to weld orientation; *d–f* — from the advancing side, their flanging direction is normal and from the retreating side — parallel to weld orientation; *g–i* — from the advancing side and from the retreating side their flanging direction is parallel to weld orientation; *j*, *k* — from the advancing side their flanging direction is parallel and from he retreating side it is normal to weld orientation

Table 1. Ultimate strength of base metal and welded joints of AMg6M aluminium alloy made by FSW

Sample orientation relative to sheet flanging direction		Ultimate strength, MPa
Base metal	Along the sheet flanging direction	368–372
	Across the sheet flanging direction	357–361
Butt welded joint	From the tool advancing side and from the retreating side sheet flanging direction is normal to weld orientation	343–350
	From the advancing side the sheet flanging direction is normal, and from the retreating side it is parallel to weld orientation	336–343
	From the advancing and the retreating side sheet flanging direction is parallel to weld orientation	335–340
	From the advancing side the sheet flanging direction is parallel, and from the retreating side it is normal to weld orientation	338–344
Fillet welded joint	From the tool advancing side and from the retreating side sheet flanging direction is normal to weld orientation	342–347
Overlap welded joint	From the tool advancing side and from the retreating side sheet flanging direction is normal to weld orientation	337–341

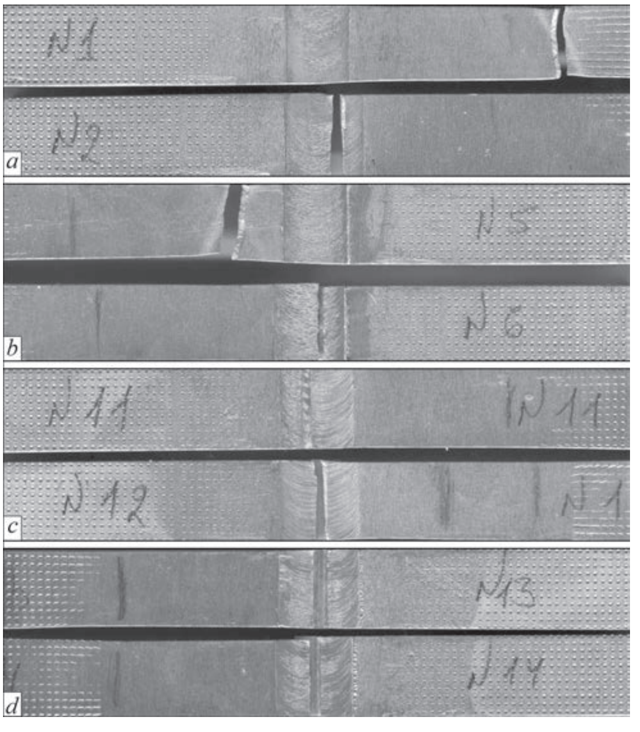

Figure 10. Appearance of the face of broken samples of fillet joints of AMg6M alloy produced by butt (*a*, *b*) and overlap-butt (*c, d*) welds with 12.0 mm sheet placed from the advancing (*a*, *c*) and the retreating side (*b*, *d*)

metal strength is lower under such conditions (Figure 9, *d–f*).

For butt joints, where the sheet flanging direction is parallel to weld orientation both from the advancing and the retreating sides, the ultimate strength is equal to 335–340 MPa. This parameter is close by its value to the previous variant of sheet arrangement, as the samples fail in the same zones, and base metal strength at such an arrangement of the sheets is lower (Figure 9, *g–i*).

Now, if from the advancing side the sheet flanging direction is parallel, and from the retreating side it is normal relative to the weld orientation, the ultimate strength of samples of such joints is on the level of 338–344 MPa. At their static stretching, the samples fail through the base material from the advancing side, where the forces are oriented normal to the sheet flanging direction, or on the boundary of the thermomechanical impact zone and heat-affected zone from the retreating side (Figure 9, *j*, *k*).

Testing of samples of fillet joints made by butt welds showed that at their static stretching, fracture usually runs through the base metal (sometimes, in the thermomechanical impact zone in the area of weld-to-base metal transition), irrespective of the position of the sheets being welded (Figure 10 *a*, *b*). Here, the ultimate strength of such welded joints is in the range of 342–347 MPa.

Fillet welded joints, made by overlap-butt welds, at static stretching fail in the thermomechanical impact zone in the area of weld metal fusion with base metal (Figure 10 *c*, *d*) and their ultimate strength is on the level of 337–341 MPa.

The generalized results from experimental data of studying the strength of base metal and welded joints of AMg6M aluminium alloy, produced by FSW, are given in the Table 1, depending on the sheet flanging orientation.

CONCLUSIONS

1. At FSW of butt, overlap and fillet joints of AMg6M aluminium alloy a weld nugget with a fine-crystalline

structure forms in the central part of the welds as a result of intensive plastic deformation of the metal. The size of the grains having a practically globular shape, is not more than 4–5 μm, and that of phase precipitates is ≤ 1 μm. In the thermomechanical impact zone on the fusion boundary of the weld and base materials, partial metal deformation takes place, so that in addition to fine grains, somewhat larger (6–7 μm) elongated grains form, oriented along the direction of plasticized metal displacement by the tool working surfaces. Here, in the HAZ, where the metal was not exposed to deformational impact, the maximal size of its grains is on the level of 10–15 μm.

2. The ultimate strength of samples of butt joints and fillet joints produced by butt and overlap-butt welds is on the level of 335–350 MPa at their static stretching, and it is practically independent of the position of the sheets being welded, either from the advancing side or the retreating side or weld orientation relative to their flanging direction. Here, butt joint samples fail mainly through the base metal, or on the boundary of the thermomechanical impact zone and the heat-affected zone. Samples of fillet joints, produced by overlap-butt welds, fail in the thermomechanical impact zone, and those made by butt welds fail also through the base metal.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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