DOI: https://doi.org/10.37434/tpwj2023.04.01

MECHANICAL PROPERTIES AND STRUCTURAL FEATURES OF BUTT JOINTS PRODUCED AT FSW OF ALUMINIUM ALLOYS OF DIFFERENT ALLOYING SYSTEMS

A.G. Poklyatskyi[1], S.I. Motrunich[1], V.Ye. Fedorchuk[1], Iu.V. Falchenko[1], M. Sagul[2]

[1]E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
[2]Czech Technical University
16636, Prague, Czech Republic

ABSTRACT

The paper presents the results of investigations of the strength, hardness and structure of butt joints on aluminium alloys of different alloying systems, produced by friction stir welding (FSW). It is shown that this process allows producing sound joints of aluminium alloys of different alloying systems, both in similar and dissimilar combinations. This is true not only for aluminium alloys made by casting by the standard technological scheme, but also for granulated alloys, containing the oversaturated solid solution of refractory transition metals, produced by powder metallurgy. It is found that the strength of welded joints produced at FSW of aluminium alloys, depends on the chemical compositions and mechanical properties of these alloys. Maximum ultimate strength is demonstrated by welded joints of the following high-strength alloys: 1995 (483 MPa), 1963 (473 MPa) and D16 (441 MPa), which is due to a slight degree of metal softening in the thermomechanical impact zone (TMIZ), which is where the samples fail at mechanical stretching. Destruction of samples of welded joints of dissimilar aluminium alloys also runs in this zone or on its boundary with the heat-affected zone (HAZ) from the side of the softer alloy. Their ultimate strength is on the level of the joints of the respective similar alloys. It is shown that intensive plastic deformation of metal at FSW of dissimilar aluminium alloys results in formation of grains of practically globular shape in the weld nugget in the permanent joint zone, their size not exceeding 4–6 μm. In granulated alloy welding, the oversaturated solid solution is preserved in the granules, just their mechanical refinement takes place, resulting in a fine dense structure of the weld nugget, and the granules containing an oversaturated solid solution of refractory transition metals, are uniformly distributed over the entire volume of the matrix in the weld metal.

KEYWORDS: aluminium alloys, friction stir welding, hardness, strength, structure

INTRODUCTION

Aluminium alloys are widely used in manufacture of diverse flying vehicles, watercraft, railway, wheeled and tracked transport, building and bridge structures. This is largely due to obvious advantages of aluminium, compared to other structural materials: it is three times lighter than steel, has high corrosion resistance and electric conductivity, features considerable specific strength, antimagnetism and absence of cold-shortness threshold. Here, the majority of aluminium alloys are readily treatable and they can weld well that allows their application in manufacture of various structural components [1].

Depending on the functional purpose of such components, the required semi-finished products and respective alloying systems and compositions of aluminium alloys are selected for their manufacture. The world market proposes to users approximately three hundred compositions of structural aluminium alloys, which have different physicomechanical properties and are produced in the form of bars, flat, profiled, and extruded profiles, wires and foil [2, 3].

In addition to conventional aluminium alloys produced by the standard casting technology, the fraction of composite materials is growing in the proposed kinds of semi-finished products. These composite materials contain reinforcing particles of Al_2O_3 aluminium oxide, or SiC silicon carbide [4, 5]. It provides high values of the modulus of elasticity, wear and high-temperature resistance, as well as low values of specific weight and coefficients of thermal expansion and friction. Granulated aluminium alloys take up a significant place in the range of structural alloys, owing to application of powder metallurgy achievements. During their production it is possible to essentially increase the level of alloy doping by such refractory transition metals as chromium, zirconium, titanium, vanadium, etc., owing to a high rate of granule cooling during crystallization. At granule crystallization, these metals form anomalously oversaturated solid solutions. At further technological heating, dispersed intermetallics form owing to decomposition of such solid solutions, which ensures a significant hardening of the alloys [6, 7]. Creation of quasicrystalline materials should be noted among new achievements in the

Table 1. Chemical composition of the studied aluminium alloys

Alloy grade	Weight fraction of chemical elements, % (balance — Al)											
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Li	Sc	Other
AMg5M	0.50	0.50	0.10	0.7	5.2	–	0.20	0.09	–	–	–	0.05 Be
AMg6M	0.40	0.40	0.10	0.8	6.3	–	0.20	0.10	–	–	–	0.05 Be
D16	0.50	0.50	4.5	0.7	1.6	0.10	0.25	0.15	0.05	–	–	–
1460	0.10	0.15	3.1	0.1	0.1	0.05	0.25	0.06	0.12	2.3	0.12	0.08 Be
6013	0.58	0.20	0.95	0.26	1.0	–	–	0.03	–	–	–	–
1963	0.15	0.25	1.9	–	2.9	–	6.8	–	0.15	–	–	–
1995	0.15	0.20	–	0.23	2.8	0.65	4.95	0.20	–	–	–	–
1419	0.15	0.20	–	2.0	–	1.05	–	0.60	0.60	–	–	0.60 V

sphere of manufacturing modern aluminium alloys. They contain intermetallics in the form of nanosized quasicrystalline particles, which ensure high physico-mechanical properties of such materials [8, 9].

However, realization of potential possibilities of such promising materials in welded structure fabrication largely depends on correct selection of the methods to produce sound permanent joints. While various welding processes are used with success for the majority of batch-produced alloys, the above-mentioned advanced materials require application of solid state welding so as to preserve the advantages of parent material in the welds [5, 10, 11].

Selection of materials during manufacture of welded structure components largely depends on their functional purpose and operating conditions. Therefore, in order to ensure certain properties of individual elements or components, it is necessary to weld not only similar, but also dissimilar aluminium alloys, which may differ both by the alloying system, and by their production method [3].

The objective of this work is evaluation of the effectiveness of application of friction stir welding (FSW) to produce sound joints of dissimilar aluminium alloys, including granulated ones.

MATERIALS, PROCEDURES AND EQUIPMENT

Aluminium alloys 2 mm thick of different alloying systems were used for investigations. Their composition is given in Table 1. Among the presented materials are common alloys (AMg5M, AMg6M and D16), advanced high-strength alloys (1460 and 1963) and 6013 alloy of increased high-temperature resistance, which were produced by the standard technological scheme, as well as 1995 and 1419 alloys produced using powder metallurgy. Mechanical properties of the studied alloy sheets are given in Table 2.

Table 2. Mechanical properties of the studied aluminium alloys

Alloy grade	Ultimate strength σ_t, MPa	Yield limit $\sigma_{0.2}$, MPa	Relative elongation δ,%	Bend angle α, deg
AMg5M	338	161	21.8	180
AMg6M	359	220	22.3	96
D16	445	315	18.5	83
1460	486	445	17.7	37
6013	410	317	8.0	96
1963	560	530	6.3	54
1995	610	527	7.1	26
1419	300	260	12.8	115

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

FSW was performed in a laboratory unit developed at PWI at tool rotation frequency N = 1420 rpm, using a special tool with the shoulder of 12 mm diameter, and 1.85 mm long tip in the form of a truncated cone with 3.4 mm diameter at the shoulder base and 12° angle of inclination of the cone generatrix [12]. The produced welded joints were used to make sections for studying their structural features. The ultimate strength of welded joints was determined at static uniaxial tension of standard flat samples with 15 mm width of the working zone in an all-purpose servohydraulic system MTS 318.25. Structural features of the welded joints were evaluated using optical electron microscope MMT-1600B. Metal hardness in different zones of the produced butt welded joints was measured on the sample face surfaces in ROCKWELL instrument at loading P = 600 N.

INVESTIGATION RESULTS AND DISCUSSION

Conducted experimental studies showed that sound formation of aluminium alloy welds at FSW is ensured at different rates of linear displacement of the tool. So, optimal welding speed for AMg5M alloy at tool rotation frequency of 1420 rpm is equal to 16 m/h, and for 1460 alloy — 14 m/h, for AMg6M alloy — 12 m/h, and for D16 alloy it is 10 m/h. Sound welded joints of 6013 alloy can be produced at welding speed of

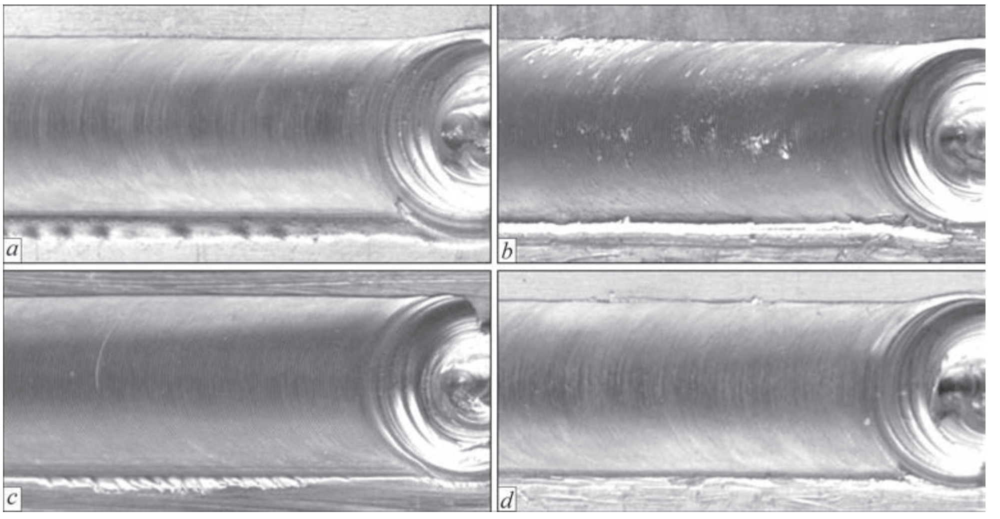


Figure 1. Appearance of the face surface of welds produced at FSW in the optimal modes of aluminium alloys in a similar combination: *a* — 6013; *b* — 1963; *c* — 1995; *d* — 1419

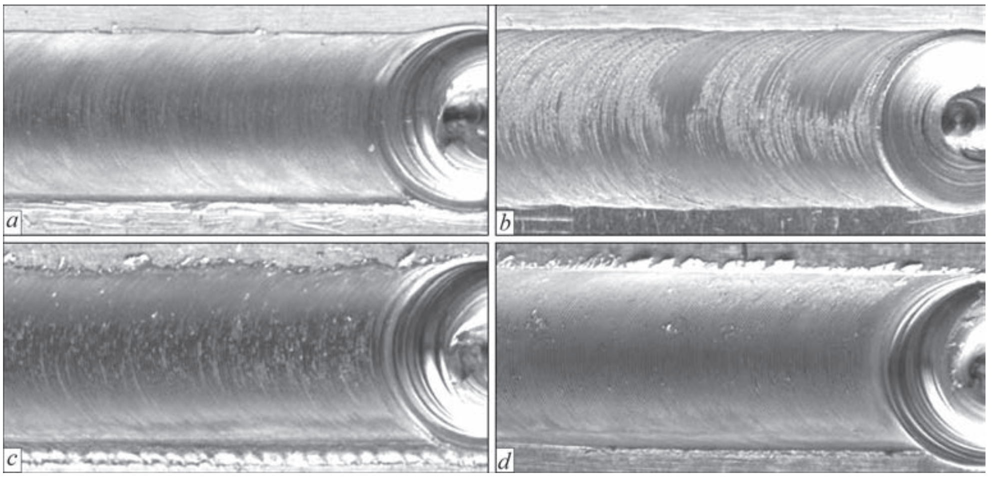


Figure 2. Appearance of the face surface of welds produced by FSW in the optimal modes of aluminium alloys in dissimilar combinations: *a* — AMg6M + 6013; *b* — AMg6M + 1419; *c* —1460 + 6013; *d* — 1460 + 1995 (the first specified alloy is placed on top — from the advancing side)

38 m/h, those of 1963 alloy — 10 m/h, 1995 and 1419 alloys — 26 m/h. Appearance of such welded joints is given in Figure 1.

Results of experimental studies showed that in order to produce sound joints of dissimilar aluminium alloys, FSW should be performed at a smaller speed of the tool linear displacement for the selected alloy pair that allows reducing the probability of development of internal weld defects in the form of discontinuities. Appearance of some sound butt welded joints of aluminium alloys in the dissimilar combination, produced by friction stir welding, is given in Figure 2.

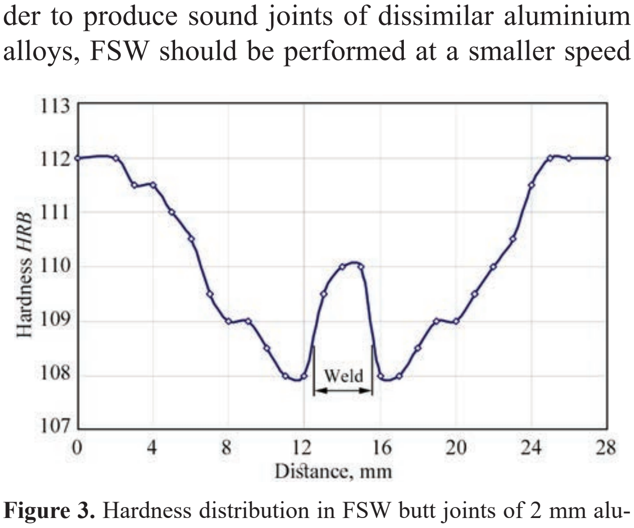


Figure 3. Hardness distribution in FSW butt joints of 2 mm aluminium alloy 1963

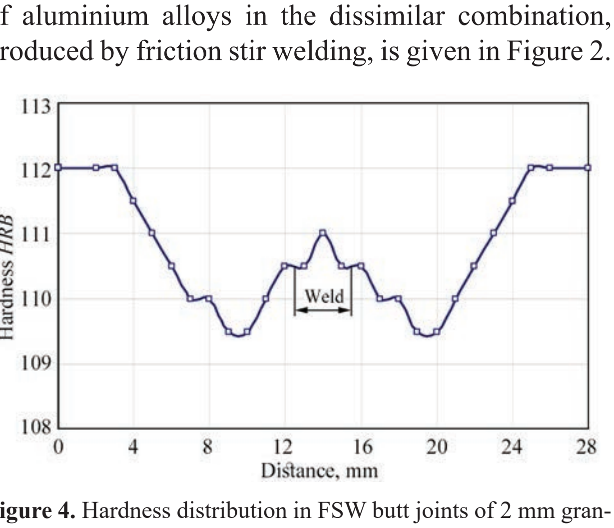


Figure 4. Hardness distribution in FSW butt joints of 2 mm granulated aluminium alloy 1995

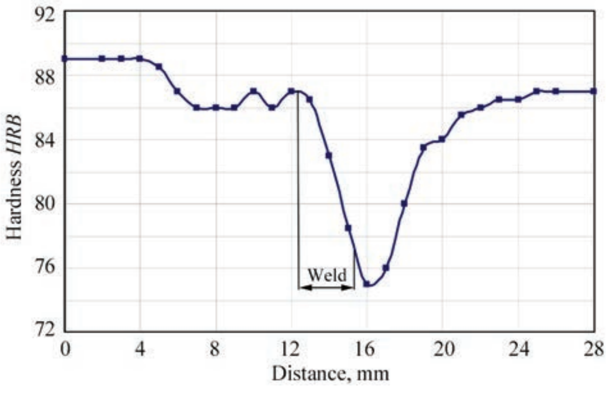


Figure 5. Hardness distribution in butt joints, produced at FSW of AMg6M alloy (left) to 1419 alloy (right) 2 mm thick

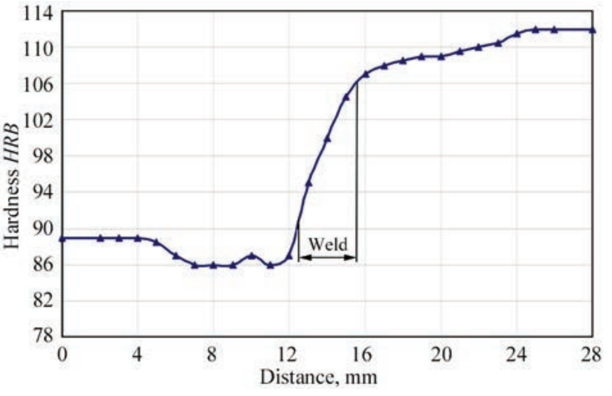
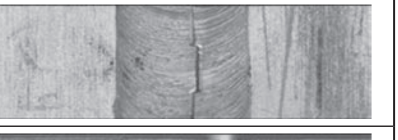
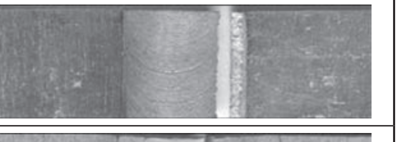
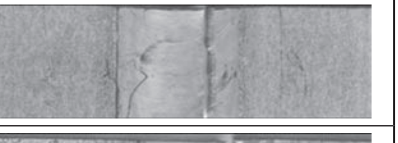
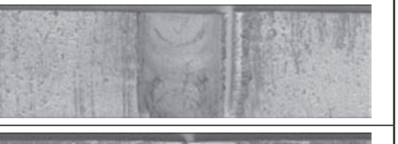
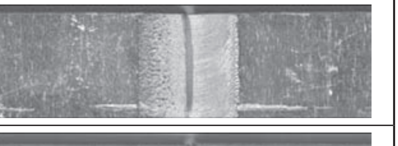
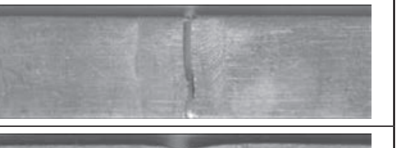
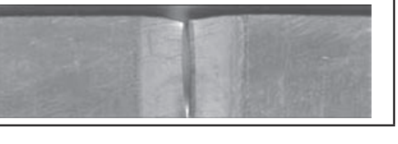


Figure 6. Hardens distribution in butt joints produced at FSW of AMg6M alloy (left) to 1963 alloy (right) 2 mm thick

Measurements of metal hardness in the welding zone showed that the degree of its softening depends on the aluminium alloy chemical composition. Here, for the majority of the alloys weld metal hardness is somewhat higher, that in the thermomechanical impact zone (TMIZ), due to formation of a fine-crystalline metal structure. So at FSW of 6013 alloy with a higher corrosion resistance the weld metal hardness is equal to *HRB* 87–88, and in TMIZ it is *HRB* 85–86. For high-strength 1963 alloy of Al–Cu–Mg–Zn alloying system the maximum degree of metal softening is also observed in the TMIZ, whereas in the weld it is on the level of *HRB* 109–110 (Figure 3).

Ductile low-alloyed granulated 1419 alloy has the hardness of weld metal and adjacent regions on the level of *HRB* 75–76, whereas for the base metal it is

Table 3. Ultimate strength of butt joints produced at FSW of similar aluminium alloys

Number	Alloy grade	Ultimate strength, MPa	Fracture site	Broken sample photo
1	AMg5M	315 <u>310</u> 313	HAZ TMIZ	
2	AMg6M	334 <u>329</u> 332	HAZ TMIZ	
3	D16	443 <u>439</u> 441	TMIZ/HAZ_{ret}	
4	1460	310 <u>307</u> 309	TMIZ	
5	6013	238 <u>230</u> 234	TMIZ/HAZ_{ret}	
6	1963	482 <u>462</u> 473	TMIZ	
7	1995	490 <u>478</u> 483	TMIZ	
8	1419	257 <u>253</u> 255	TMIZ	

equal to *HRB* 87 (Figure 6). At FSW of high-strength granulated 1995 alloy the degree of metal softening in the welding zone is quite small: in the weld metal hardness is equal to *HRB* 110.5–111.0, whereas for the base metal it is on the level of *HRB* 112, and in TMIZ it is equal to *HRB* 109.5–110.5 (Figure 4).

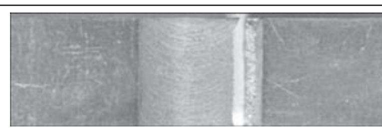
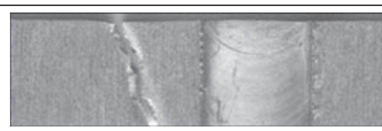
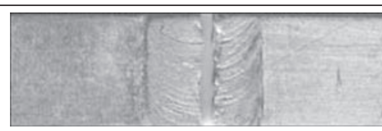
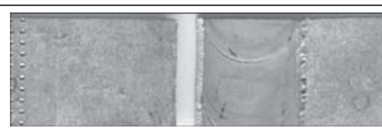
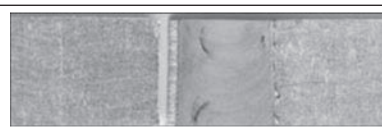
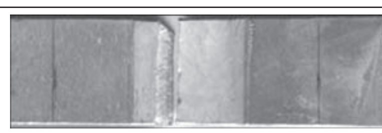
Measurements of metal hardness in the zone of formation of permanent joints, produced at dissimilar combination of aluminium alloys showed that compared to welding of similar alloys changes in metal hardness occur only in the welds and regions adjacent to them in TMIZ. So, for instance, in welding AMg6M alloy to 1419 alloy, the weld metal hardness from AMg6M side is equal to *HRB* 85–87, and from 1419 side it is *HRB* 77–79 (Figure 5).

Welding of AMg6M alloy to high-strength 1963 alloy ensures weld metal hardness on the level of *HRB* 90–95 from AMg6M side, and from 1963 side it is *HRB* 104–106 (Figure 6), while minimal metal hardness (*HRB* 86) is observed in TMIZ from the side of AMg6M alloy, as it is for similar joints of this alloy.

A similar situation is observed also in welding other studied joints of dissimilar aluminium alloys: an abrupt change of weld metal hardness or its smooth transition at a combination of dissimilar alloys take place. So, an abrupt change of weld metal hardness takes place in welding the following alloys to each other: AMg5M + 1995, AMg6M + 1963, AMg6M + 1419, 1460 + 6013 and 1460 + 1995, whereas the combination of AMg6M + 6013, D16 + 1963 and D16 = 1995 alloys ensures a smooth change of metal hardness in the joint zone. For instance, in welding AMg5M alloy to 1995 alloy weld metal hardness from the side of AMg5M alloy is on the level of *HRB* 84–90, whereas from the side of 1995 alloy it is much higher (*HRB* 104–108). In welding AMg6M alloy to 6013 alloy the weld metal hardness is approximately the same from both the sides (*HRB* 87–89).

Experimental studies revealed that at FSW of aluminium alloys in a similar combination, the strength of their welded joints and sample fracture site depend on the chemical compositions and mechanical proper-

Table 4. Ultimate strength of butt joints produced at FSW of dissimilar aluminium alloys

Number	Alloy grade	Ultimate strength, MPa	Fracture site	Broken sample photo
1	AMg5M + 1995	316 309 314	HAZ_{AM5M} $TMIZ_{AM5M}$	
2	AMg6M + 6013	236 231 234	TMIZ /HAZ_{6013}	
3	AMg6M + 1963	336 330 333	HAZ_{AMg6M} $TMIZ_{AMg6M}$	
4	AMg6M + 1419	259 252 256	$TMIZ_{1419}$	
5	D16 + 1963	445 440 442	TMIZ/HAZ_{D16}	
6	D16 + 1995	442 439 440	TMIZ/HAZ_{D16}	
7	1460 + 6013	237 232 234	TMIZ/HAZ_{6013}	
8	1460 + 1995	312 306 309	$TMIZ_{1460}$	

ties of the welded alloys (Table 3). In most cases the welded joint samples fail in TMIZ. Some samples of AMg65M and AMg6M alloys fail in the HAZ. Now, for D16 and 6013 alloy joints the characteristic site of sample destruction is the boundary between TMIZ and HAZ from the retreating side (HAZ_{ret}).

So, the maximum ultimate strength is found in welded joints of high-strength 1995 (483 MPa), 1963 (473 MPa) and D16 alloys (441 MPa) that is due to a slight (*HRB* <2.5) degree of metal softening in TMIZ, which is where the samples fail at static tension. At FSW of high-strength 1460 alloy a rather significant softening (*HRB* 24) of the metal takes place in the zone of permanent joint formation, resulting in ultimate strength of its welded joints being on the level of 309 MPa. Welded joints of 1419 (255 MPa) and 6013 alloys (234 MPa) have minimal ultimate strength that is also due to a high (≈ *HRB* 12) degree of metal softening in TMIZ and lower strength of the base material.

At FSW of aluminium alloys in a dissimilar combination, the welded joint strength and sample destruction site also depend on the chemical composition and mechanical properties of the materials being welded (Table 4).

So, in welding AMg5M or AMg6M alloys to high-strength 1995 and 1963 alloys, which are only slightly softened here, the joint sample fracture runs in the HAZ or TMIZ from the side of AMg5M or AMg6M alloys, and their strength is the same, as in welding these alloys in a similar combination. The same regularities are preserved also in welding other alloys. For instance, welded joints of 1460 + 1995 alloys fail in TMIZ, and those of D16 + 1963 and D16 + 1995 alloys — on the boundary of TMIZ and HAZ from the side of 1460 and D16 alloys, which have lower strength. The ultimate strength of such joints of dissimilar alloys is on the level of joints of the respective similar alloys. Samples of joints, produced at FSW of AMg6M alloy to 6013 and 1419 alloys fail on the boundary of the HAZ and TMIZ from the side of lower-strength alloys.

As a result of experimental studies it was determined that in solid state friction stir welding of the above-mentioned aluminium alloys in a similar combination, grain refinement takes place in the zone of permanent joint formation as a result of intensive plastic deformation of the metal. In welding of alloys produced by the standard casting technology, grains

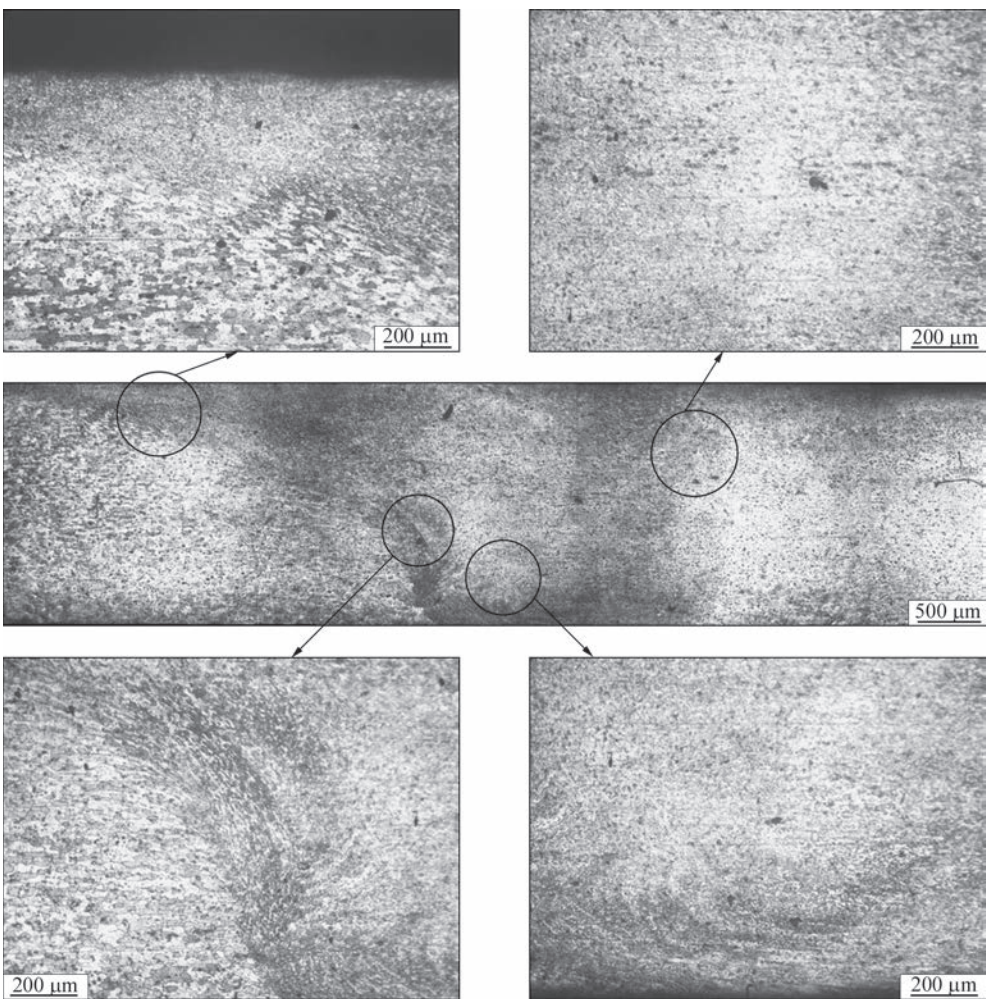


Figure 7. Microstructure of welded joint of 2 mm aluminium alloy 6013, produced by FSW

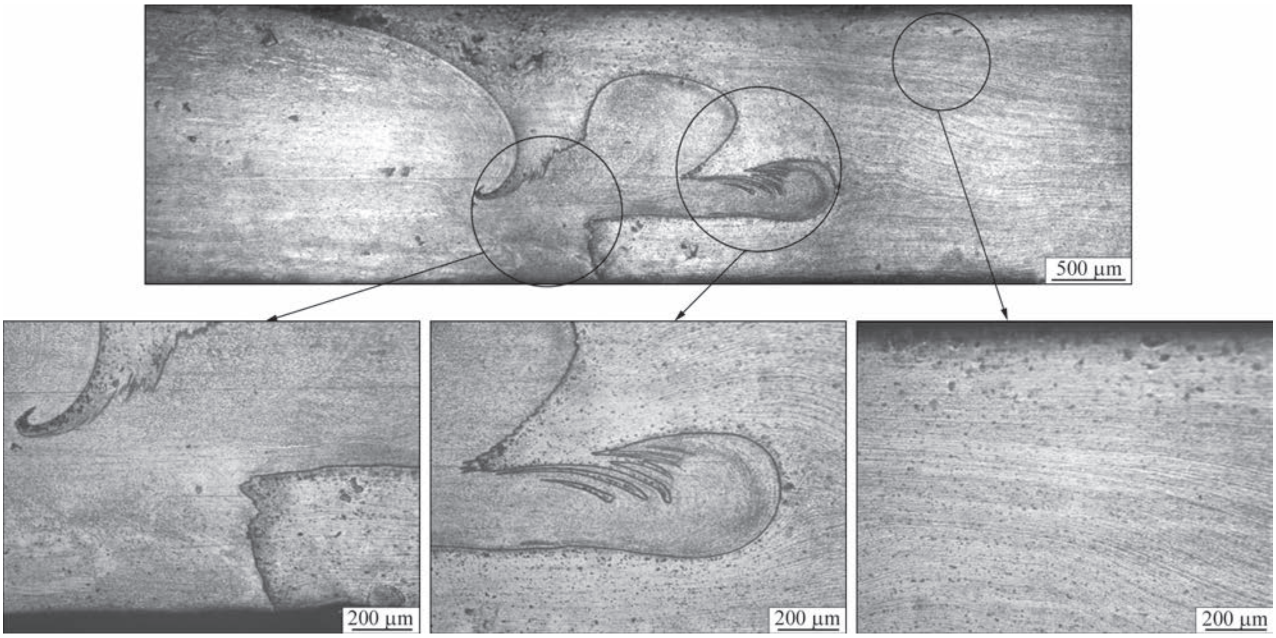


Figure 8. Microstructure of a 2 mm dissimilar welded joint produced at FSW of 1460 aluminium alloy (left) to granulated 1995 aluminium alloy (right)

of a practically globular shape form in the weld nugget, the size of which does not exceed 4–6 μm. In the zone of thermomechanical impact along the boundaries of the weld to base metal transition a more coarse-grained structure (6–8 μm) is observed, compared to the weld nugget, and most of the grains are elongated in the direction of the tool rotation. Here, a more abrupt change of the direction of grain orientation is found from the advancing side, where the directions of rotation and linear displacement of the tool coincide, than from the opposite retreating side. In HAZ the base material structure is preserved, and no surface melting of the structural components takes place (Figure 7). In granulated alloy welding the oversaturated solid solution is preserved in the granules, just their mechanical refinement takes place, resulting in the weld nugget having a finely dispersed dense structure of the weld, and in the zone of weld to base material transition just the direction of the rolling stock texture changes under the impact of the rotational and translation movement of the welding tool.

At FSW of aluminium alloys in a dissimilar combination the welded joint structure changes. Complete mixing of the materials being joined is observed only in the weld upper part, which is equal to 20–25 % of their thickness. In the weld center and lower part individual regions of completely unmixed volumes of the alloys being welded are readily visible. These regions formed as a result of plastic deformation of the metal and its mass transfer by the working surfaces of the tool tip and shoulder. Here, the grain dimensions in the weld central part are approximately the same, as at FSW of the studied alloys in a similar combination, which is indicative of an intensive plastic deformation of the metal. In TMIZ of dissimilar welded joints, slight differences from similar joints are observed, which are also partly caused by the presence of completely unmixed metal volumes, and partly — by a change in the conditions of weld formation, as a result of different ductility of the alloys being welded. The base metal structure in the HAZ does not change (Figure 8).

CONCLUSIONS

1. Weld formation in the solid state welds at FSW allows producing sound permanent joints of aluminium alloys of different alloying systems, both in the similar and dissimilar combinations. This is true not only for aluminium alloys produced by the standard casting technology, but also for granulated alloys, containing an oversaturated solid solution of refractory transition metals, manufactured using powder metallurgy.

2. Degree of metal softening in the welds depends on the chemical composition of aluminium alloys and their heat hardening ability. The minimal difference between base metal and weld metal hardness is observed at FSW of granulated aluminium alloy 1995 ($HRB \leq 1.5$) and high-strength aluminium alloy 1963 ($HRB \leq 3.5$), prone to hardening in the air. In welding common heat-hardened aluminium alloys 6013 and 1419 weld metal hardness is much ($HRB > 9$) lower than that of the base metal. In joints produced at a dissimilar combination of aluminium alloys, an abrupt or smooth change of hardness at transition from one alloy to another one is observed in the weld metal, depending on the degree of softening of the alloys being welded.

3. Strength of welded joints, produced at FSW of aluminium alloys both in similar and dissimilar combinations, depends on chemical compositions and mechanical properties of these alloys. The maximum ultimate strength is found in welded joints of high-strength 1995 (483 MPa), 1963 (473 MPa), and D16 (441 MPa) alloys that is due to a slight degree of metal softening in TMIZ, which is where the samples fail at static tension. Destruction of samples of welded joints of dissimilar aluminium alloys runs in TMIZ or on the boundary of TMIZ and HAZ from the side of the lower strength alloy. Their ultimate strength is on the level of joints of the respective similar alloys.

4. AT FSW of aluminium alloys both in similar and dissimilar combinations, grains of a practically globular shape, the size of which does not exceed 4–6 μm, form in the weld nugget, owing to intensive plastic deformation of the metal in the permanent joint zone. In welding granulated alloys, the oversaturated solid solution is preserved in the granules, and just their mechanical refinement takes place. As a result, the weld nugget has a finely dispersed dense structure, and the refractory alloying elements do not precipitate from the solid solution in the form of aluminides, which can significantly lower the properties of welded joints of such alloys.

REFERENCES

1. Ishchenko, A.Ya., Labur, T.M. (2013) *Welding of modern structures from aluminium alloys.* Kyiv, Naukova Dumka [in Russian].
2. Ishchenko, A.Ya., Labur, T.M., Bernadsky, V.M., Makovetskaya, O.K. (2006) *Aluminium and its alloys in modern welded structures.* Kyiv, Ekotekhnologiya [in Russian].
3. Beletsky, V.M., Krivov, G.A. (2005) *Aluminium alloys (Composition, properties, technology, application)*: Refer. Book. Ed. by I.N. Fridlyander. Kyiv, KOMINTEKh.
4. Ryabov, V.R., Pavlenko, Yu.V. (1991) Welding of composite materials (Review). *The Paton Welding J.*, **3**, 46–56.
5. Ishchenko, A.Ya., Kharchenko, G.K., Falchenko, Yu.V. et al. (2006) Vacuum solid phase joint of dispersion-hardened composite materials. *Nanosistemy, Nanomaterialy, Nanotekhnologii,* **3**, 747–756 [in Russian].
6. Yasuhiro, Uetani, Ryotaro, Nagata, Hidetoshi, Takadi et al. (2007) Effect of granule size in semi-solid slurry on rheo-extrusion of A7075 aluminum alloy. *Mat. Sci. Forum*, **561–565**, 291–294. DOI: https://doi.org/10.4028/www.scientific.net/MSF.561-565.291
7. Guojiang, Dong, Changcai, Zhao, Yaxin, Peng, Ying, Li (2015) Hot granules medium pressure forming process of AA7075 conical parts. *Chinese J. of Mechanical Eng.,* **28**, 580–591. DOI: https://doi.org/10.3901/CJME.2015.0217.019
8. Inoue, A., Kimura, H. (2000) High-strength aluminium alloys containing nano-quasicrystalline particles. *Mater. Sci. and Eng*. **1**, 1–10.
9. Milman, Yu.V., Sirko, A.I., Yefimov, M.O. et al. (2006) High-strength alloys reinforced by nanosize quasi-crystalline particles for elevated temperature application. *High-Temperature Materials and Processes*, **1–2**, 19–29.
10. Poklyatsky, A.G., Ishchenko, A.Ya., Fedorchuk, V.E. (2011) Friction stir welding of composite, granulated and quasicrystalline aluminium alloys. *The Paton Welding J.*, **7**, 2–7.
11. Milman, Yu.V., Zakharova, N.P., Yefimov, M.O. et al. (2019) Structure and mechanical properties of welded joints of Al–Cr–Fe–Ti system with quasi-crystalline phase. *Elektronnaya Mikroskopiya i Prochnost Materialov,* **25**, 17–26 [in Russian].
12. Ishchenko, A.Ya., Poklyatsky, A.G. (2010) *Tool for friction stir welding of aluminium alloys*. Pat. 54096, Ukraine, Int. Cl. B23K 20/12; Fill. 30.04.2010, Publ. 25.10.2010 [in Ukrainian].

ORCID

A.G. Poklyatskyi: 0000-0002-4101-2206,
S.I. Motrunich: 0000-0002-8841-8609,
V.Ye. Fedorchuk: 0000-0002-9929-3231,
Iu.V. Falchenko: 0000-0002-3028-2964,
M. Sagul: 0000-0001-5091-6381

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

S.I. Motrunich
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: paton.testlab@gmail.com

SUGGESTED CITATION

A.G. Poklyatskyi, S.I. Motrunich, V.Ye. Fedorchuk, Iu.V. Falchenko, M. Sagul (2023) Mechanical properties and structural features of butt joints produced at FSW of aluminium alloys of different alloying systems. *The Paton Welding J.*, **4**, 3–10.

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 21.03.2023
Accepted: 25.05.2023