FRICTION STIR WELDING AS AN EFFECTIVE METHOD TO IMPROVE STRUCTURE PERFORMANCE*

A.A. POKLYATSKY, A.Ya. ISHCHENKO, A.A. CHAJKA and **T.M. LABUR**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Main advantages of weld formation in the solid phase as a result of plastic deformation of metal in friction stir welding of auminium alloys are considered. Examples of using this process in the developed countries to produce welded structures in various engineering sectors and the resulting saving of the resources are given. Structures, weakening degree, strength, values of resistance to off-center tension of samples, and levels of residual stresses and strains in high-strength aluminium alloy welded joints produced by friction stir welding and nonconsumable-electrode argon-arc welding are analyzed.

Keywords: *high-temperature aluminium alloys, friction stir welding, nonconsumable-electrode argon-arc welding, microstructure, hardness, strength, off-center tension*

The main characteristic of any industrial structure is the ability to ensure the required performance under specified service conditions for a certain period of time. New materials, unique production technologies and different methods of joining individual elements and components often have to be used in structure fabrication to achieve the set objective. Each of these components has an essential influence on the finished product cost and largely determines their operating characteristics.

Wrought and heat-hardenable aluminium alloys are rather widely used as structural materials. Owing to high specific strength, good corrosion resistance, reliable resistance to repeated loads and low rate of fatigue crack propagation, these materials are used in development of aviation systems, space vehicles, water and land transportation [1–3]. Various welding processes are used to produce permanent joints in fabrication of aluminium alloy structures. In most of the cases, however, weld formation occurs due to melting of a certain volume of the metal being welded and filler wire fed into the welding zone with their subsequent solidification in an inert shielding atmosphere. Metal heating up to melting temperature leads to significant phase and structural transformations, causing considerable plastic deformation of the joints, and promotes development of high residual stresses in them. In the welding zone the base metal softens, and the weld has a cast coarse-crystalline structure, leading to an abrupt lowering of the welded joint ultimate strength. In addition, during melt solidification intercrystalline fracture of welds can take place in the sites of precipitation of secondary low-melting phases [4]. Therefore, many of the above drawbacks can be avoided, if the welding process is performed without metal preheating up to the melting temperature.

One of the promising methods to produce solid-phase permanent joints is friction stir welding (FSW). Here the principle of weld formation is based on heating of a small metal volume up to the plastic state due to friction, its stirring across the entire thickness of the edges being welded, and deformation in a closed space [5]. That is why, the FSW process has a number of significant advantages compared to fusion welding [6, 7]:

- weld formation in the solid phase allows avoiding formation of hot cracks, macroinclusions of oxide film, pores and other defects, which are due to metal melting and solidification in fusion welding;
- metal heating in the welding zone due to friction eliminates ultraviolet radiation of the arc, evolution of fume and metal vapours and lowers the noise level;
- permanent joint without metal melting can be formed without shielding gas application and welding can be performed in any position in space;
- absence of an arc discharge and molten metal prevents loss of alloying elements in the weld, and eliminates the need of increasing their content in it through application of filler materials;
- stirring of plasticized metal at excess pressure in a limited volume leads to fragmentation of macroparticles of oxide inclusions, and the requirements to surface preparation of the edges being welded become less stringent;
- tool tip penetration to the entire depth of the butt allows welding metal of different thickness without any special edge preparation;
- running of the welding process at lower temperatures leads to reduction of the degree of material softening and level of residual deformations in structures;
- increased effectiveness of energy utilization at FSW and reduction of metal heating temperature in

*The paper was prepared by the results of fulfillment of comprehensive program of the NAS of Ukraine «Problems of life and safety of operation of structures, constructions and machines».

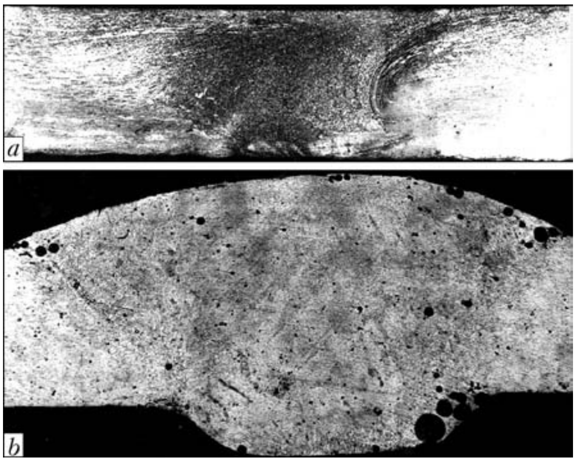

Figure 1. Transverse macrosections (×12) of welded joints of aluminium alloy 1460 made by FSW (*a*) and TIG welding with Sv1201 filler (*b*)

the welding zone lower the process energy content compared to fusion welding;

• possibility of easy automation of the welding process, thus ensuring a stable quality of welds without high operator qualifications.

Owing to such advantages FSW process opens up wider technological capabilities for fabrication of welded structures from alloys which cannot be joined by fusion welding because of formation of hot cracks in welds; ensuring a higher strength level of welded joints on heat-hardenable and work-hardened aluminium alloys; joining metastable alloys produced by rapid solidification of metal from the melt, composites and nanomaterials; producing from batch-produced individual profiles those welded components which it is not rational in terms of cost or practically impossible to produce by extrusion or casting in one piece; manufacturing practically without distortion large lightweight panels in shipbuilding, aircraft and flat wagon construction, etc.

Owing to its advantages FSW process is becoming ever wider accepted in many developed countries of the world. In shipbuilding and in railway transportation large-sized integrated panels are manufactured, which are friction stir welded from individual extruded profiles [8, 9]. In automotive industry this process is applied for manufacturing space frames of cars, motor-cycles and bicycles, truck bodies, bodies and flooring of buses, vans and trailers, elements of chassis, wheel discs, etc. [10]. Application of FSW by Boeing allowed reducing the manufacturing time of Delta rocket fuel tanks and decreasing by an order of magnitude the number of defects in welds compared to fusion welding. Eclipse Aviation company successfully applies this welding process for joining the components of the fuselage and cabin of business class five-seat plane Eclipse 500, and Airbus Company is studying the possibilities of the process in order to apply it in manufacturing the fuselage, vertical stabilizers and wings of A3xx Airbus aircraft [11]. In US NASA enterprises FSW was used to perform about half a mile of welds on the external tank of the carrier rocket of the space Shuttle [12].

The effectiveness of application of this resource-saving process is indicated by the results of statistical studies obtained in the USA. Performance of about 10 % of the entire volume of welding operations by friction stir process in 2005 allowed saving $1.35 \cdot 10^{16}$ J of energy and 20000 t of shielding gas, and the total saving was more than 4.9 bln USD, although NASA rightfully believes that the main benefit from FSW process is improvement of labour conditions of welders and personnel directly involved in welded structure fabrication [11, 12].

The purpose of the work was evaluation of operating and life characteristics of welded joints of aluminium alloys made by FSW.

Investigations were conducted using sheets 1.8 mm thick from high-strength aluminium alloys AMg6, 1201, 1420 and 1460. FSW of butt joints was performed in a laboratory system designed at PWI, using a special tool with shoulder diameter of 12 mm and conical tip. The velocity of tool rotation was 1420 rpm, and that of its linear displacement along the butt was 8–14 m/h. For comparison similar samples were welded by automatic nonconsumable-electrode argon-arc (TIG) welding with the speed of 20 m/h using MW-450 unit (Fronius, Austria) at 130–145 A current with filler wires of 1.6 mm diame-

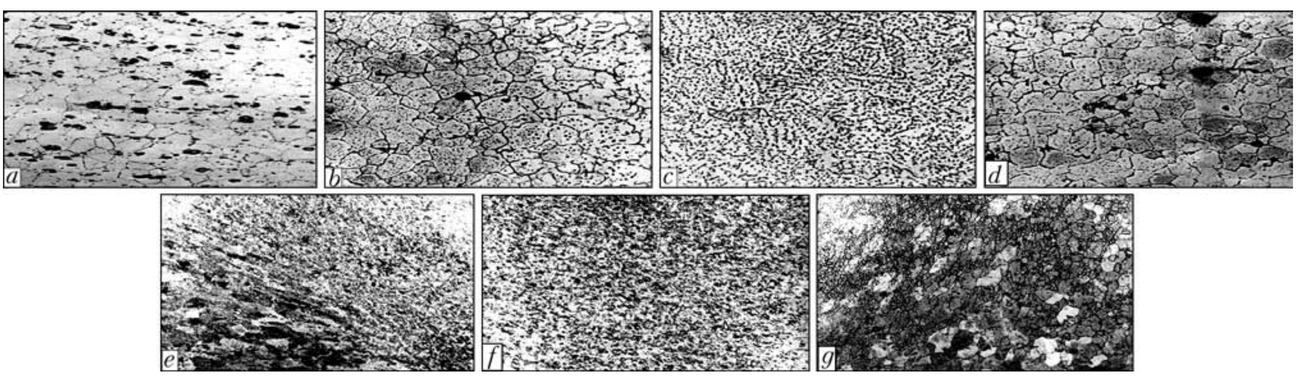

Figure 2. Microstructure (×400) of base metal (*a*) and welded joints of 1201 alloy made by TIG welding with Sv1201 filler (*b, d* — zones of fusion of weld with base metal; *c* — weld) and FSW (*e* — TMIZ from the tool advancing side; *f* — weld nugget; *g* — TMIZ from the tool retreating side)

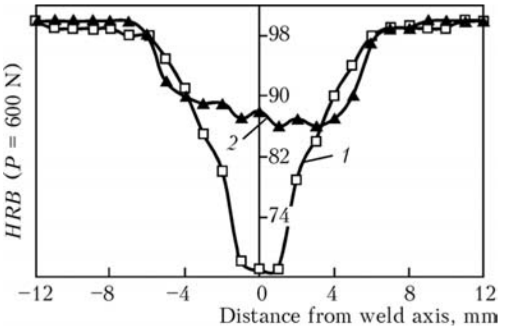

Figure 3. Metal hardness in welded joints of 1201 alloy made by TIG welding with Sv1201 filler (*1*) and FSW (*2*)

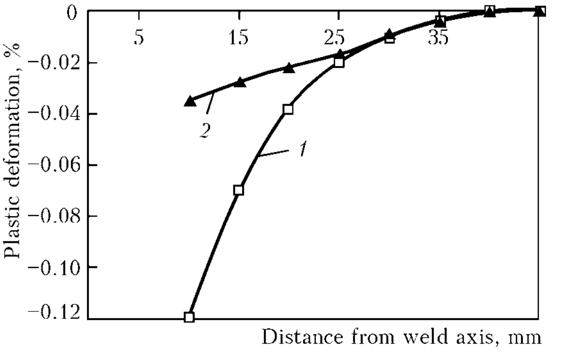

Figure 4. Plastic shrinkage deformation in welded joints of 1420 alloy made by TIG welding with SvAMg63 filler (*1*) and by FSW (*2*)

ter. Produced welded joints were used to make samples for hardness measurement, structural studies, determination of their strength at uniaxial tension and evaluation of fracture resistance values at off-center loading. Metal hardness in welded joints was measured from the side of the weld face, having first ground the reinforcement and in back bead flush with the base metal. Width of welds made by fusion welding was 6.5 mm on average, and that in FSW was 3.5 mm (at 11 mm width of the thermomechanical impact zone — TMIZ). Degree of metal softening in the welding zone was assessed by the results of its hardness measurement in ROKWELL instrument at 600 N load and sphere diameter of 1/16". Microstructure of the made joints was studied using MIM-8M optical microscope. Level of residual stresses and plastic deformations, developing in the longitudinal direction of the butt, was determined by measurement of base distance (25 mm) after welding and cutting up the samples.

Conducted experimental studies allowed assessment of the features of joints produced in the solid phase and by fusion welding. Appearance of macrosections of welds of 1460 alloy in Figure 1 shows that FSW is a resource-saving technology. Permanent joint at FSW forms only from the base metal, not requiring any filler material. It should be further taken into account that there is no need to protect the welding zone by inert gas. And since the welding process is conducted in the solid phase without metal melting, this leads to lower power consumption.

Thermomechanical conditions, under which the joints form at FSW, promote formation of a specific fine-crystalline structure of welds and adjacent sections (Figure 2). Unlike the cast structure of welds formed in fusion welding, the welds made by FSW have a deformed structure. The weld central part (nugget) forms around the tool tip at high pressure and increased temperature, resulting in dynamic recrystallization of grains and formation of fine equiaxed crystallites. In the TMIZ directly adjacent to the nugget, where the metal experiences considerable plastic deformations and heating, rather large elongated along its movement trajectory and fine recrystallized grains form. Next comes the HAZ, in which the metal was not deformed, and structural changes occurred only under the impact of heating.

Owing to formation of a deformed fine-crystalline weld structure and lower metal heating in the welding zone, the degree of softening of aluminium alloy joints is lower and ultimate strength is higher than in their fusion welding. Minimum hardness of weld metal of 1201 alloy, made by TIG welding with Sv1201 filler,

Table 1. Strength of aluminium alloy welded joints made by FSW and TIG welding

#	Welded alloys	Welding process	Filler	Tensile strength of samples without weld reinforcement σ_t^w, MPa	Strength factor $\sigma_t^w/\sigma_t^{b.m}$	Fracture site	Tensile strength of a samples with weld reinforcement σ_t, MPa	Fracture site
1	AMg6	FSW	–	332	0.92	TMIZ	–	–
		TIG welding	SvAMg6	324	0.90	Weld	345	FZ
2	1420	FSW	–	342	0.75	FZ	–	–
		TIG welding	SvAMg63	320	0.70	Weld	373	FZ
3	1201	FSW	–	310	0.73	FZ	–	–
		TIG welding	Sv1201	239	0.57	Weld	296	FZ
4	1460	FSW	–	309	0.55	TMIZ	–	–
		TIG welding	Sv1201	257	0.45	Weld	311	FZ

Note. Average values of characteristics by the results of testing 3–5 samples are given.

Table 2. Characteristics of fracture resistance at off-center loading of samples of aluminium alloy welded joints made by FSW and TIG welding

#	Welded alloys	Welding process	Filler	Tensile strength at off-center tension σ_t, MPa	Stress intensity factor K_c, MPa$\sqrt{m}$	Energy value of crack initiation J_c, J/cm^2	Specific work of crack propagation SWCP, J/cm^2
1	AMg6	–	–	402	31	7.8	6.3
		FSW	–	436	42	6.9	10.6
		TIG welding	SvAMg6	360	24	6.2	4.7
2	1420	–	–	450	15	6.5	2.7
		FSW	–	388	22	4.4	5.2
		TIG welding	SvAMg63	399	29	5.2	5.7
3	1201	–	–	486	15	6.1	2.7
		FSW	–	449	20	7.4	3.8
		TIG welding	Sv1201	333	16	3.7	2.9

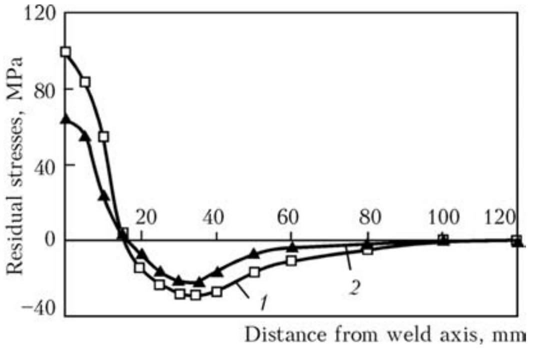

Figure 5. Residual stresses in welded joints of 1420 alloy made by TIG welding with SvAMg63 filler (*1*) and FSW (*2*)

is only *HRB* 67, and that of FS-welded metal is *HRB* 82 (Figure 3). Metal of AMg6 alloy weld made by fusion welding with SvAMg6 filler has minimum hardness *HRB* 82, and that made in the solid phase — *HRB* 87. For 1460 alloy these values are *HRB* 71 (with Sv1201 filler) and *HRB* 82, respectively. Hardness of 1420 alloy weld metal made by TIG welding with SvAMg63 filler is on the level of *HRB* 82, and that of metal welded by friction stir process is *HRB* 86.

Ultimate strength of samples without weld reinforcement made by TIG welding of AMg6 alloy with SvAMg6 filler is equal to 324 MPa, and that of samples welded by friction stir process is 332 MPa (Table 1). Here fracture of samples made by solid-phase welding occurs in the TMIZ and not in the weld metal. Welded samples of 1420 alloy, even though they fail in the weld in both the cases, have a higher ultimate strength (342 MPa) when FSW is used. An even greater difference in strength is achieved in welding copper-containing heat-hardenable aluminium alloys. Samples of 1201 and 1460 alloys made by FSW have ultimate strength on the level of 310 MPa, whereas for samples without reinforcement, made by TIG welding of 1201 and 1460 alloys with Sv1201 filler, this value is equal to just 239 and 257 MPa, respectively.

Lowering of thermal impact on the metal at FSW promotes a lowering of the level of residual plastic deformations, developing in the near-weld zone of welded joints under the impact of stresses exceeding the material proof stress. Maximum plastic deformation at metal shrinkage at 10 mm distance from weld axis is equal to 0.12 % in joints of 1420 alloy made by TIG welding, and is less than 0.04 % for joints made by FSW (Figure 4). Therefore, application of solid-phase welding promotes a lower distortion of welded structures and, therefore, allows lowering the expenses, related to its subsequent elimination.

Presence of residual plastic shrinkage deformations at weld cooling stage leads to development of residual tensile stresses in the middle part of the welded joint. Therefore, application of FSW provides a lower level of residual stresses. For instance, maximum value of residual tensile stresses in welded joints of 1420 alloy, made by TIG welding, is on the level of 99 MPa, and in those made by FSW it is 64 MPa (Figure 5), i.e. such joints are less prone to propagation of service cracks in them and have a higher fracture resistance.

A higher level of life characteristics of welded joints made in the solid phase is confirmed by the results of testing samples at their off-center tension. Samples with stress raisers in the form of a sharp (R = = 0.1 mm) notch made by FSW mostly have higher fracture resistance values than those made by a non-consumable electrode, and sometimes even higher than the respective base metal values (Table 2).

The conducted series of investigations allowed development of technological recommendations on FSW of sheet aluminium alloys. The advantages of such a process of making permanent joints will be realized in fabrication of heat exchangers and aerospace systems.

CONCLUSIONS

1. Since in FSW the weld and the adjacent sections are heated below the melting temperature of the welded metal, the possibility of solidification crack formation in aluminium alloys is eliminated.

2. Intensive stirring of plasticized metal at excess pressure in a limited space at FSW promotes formation

of an ultradispersed structure in the weld nugget, and formation of long and fine recrystallized grains elongated along the trajectory of plasticized metal displacement in the adjacent TMIZs.

3. Deformation strengthening of metal, grain refinement, increase of volume fraction of their boundaries and refinement of intermetallic phases in the weld and in the sections adjacent to it at FSW ensure a higher level of metal hardness in the welding zone and ultimate strength of joint metal than in fusion welding.

4. Lowering of thermal impact on the metal at FSW promotes a lowering of the level of residual plastic shrinkage deformations and tensile stresses in the joints, thus leading to a smaller distortion of welded structures and increasing their fracture resistance.

5. Welded joints produced by friction stir process have higher values of fracture resistance at off-center tension of samples than those made by nonconsumable electrode, and sometime even higher than the respective values for the base metal.

6. Application of resources-saving technology of producing permanent joints in the solid phase by FSW in fabrication of welded structures from aluminium alloys allows improving their operating and service life characteristics.

1. Fridlyander, I.N. (2002) Aluminium alloys in aircraft in periods of 1970–2000 and 2001–2015. *Tekhnologiya Lyog. Splavov*, **4**, 12–17.
2. Ryazantsev, V.I., Fedoseev, V.A. (1997) Welding of structures of orbital aircraft Buran. *Svarochn. Proizvodstvo*, **4**, 31–36.
3. Gorynin, I.V., Zolotarevsky, Yu.S., Rybin, V.V. et al. (1999) Metal science concepts in development of wrought aluminium alloys for high-speed sea ships. *Voprosy Metallovedeniya*, **3**, 197–209.
4. Ishchenko, A.Ya. (1985) Character of hot cracks formed in fusion welding of high-strength aluminium alloys. In: *Current problems of welding of non-ferrous metals*. Kiev: Naukova Dumka.
5. Dawes, C.J. (1995) An introduction to friction stir welding and its development. *Welding and Metal Fabr*., **1**, 13–16.
6. Dawes, C.J., Thomas, W.M. (1996) Friction stir process welds aluminum alloys. *Welding J*., **3**, 41–45.
7. Defalco, J. (2006) Friction stir welding vs. fusion welding. *Ibid*., **3**, 42–44.
8. Lahti, K. (2003) FSW — possibilities in shipbuilding. *Svetsaren*, **1**, 6–8.
9. Kallee, S.W., Davenport, J., Nicholas, E.D. (2002) Railway manufacturers implement friction stir welding. *Welding J*., **10**, 47–50.
10. Hinrichs, J.F., Norik, J.S., McDonald, W.M. et al. (2001) Challenges of welding aluminium alloys for automotive structures. *Svetsaren*, **12**, 281–287.
11. Arbegast, W.J. (2006) Friction stir welding after a decade of development. *Welding J*., **3**, 28–35.
12. Ding, J., Carter, R., Lawless, K. et al. (2006) Friction stir welding flies high at NASA. *Ibid*., **3**, 54–59.