FRICTION STIR WELDING OF ALUMINUM ALLOYS OF DIFFERENT ALLOYING SYSTEMS

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Comparative analysis of the degree of weakening and level of strength of the 1.8 mm thick TIG- and FS-welded joints on dissimilar high-strength multi-component aluminum alloys AMg6M, 1420, 1201 and 1460 was carried out. Peculiarities of formation of the weld structure in both cases were studied. It is shown that strain hardening of the welds on high-strength multi-component aluminum alloys in friction stir welding provides their higher strength level, compared with that in fusion welding.

Keywords: *friction stir welding, TIG welding, high-strength aluminum alloys, composite joints, degree of weakening, tensile strength, structure of welded joint metal*

Aluminum alloys of different alloying systems are widely used in manufacture of welded structures. Different methods of fusion welding based on weld metal crystallization from a weld pool melt are used for obtaining permanent joints. High-temperature heating of a welding zone results in structural and phase transformations in the weld metal itself as well as in the areas adjacent to it. In this connection, strength of weld metal and welded joints on cold-worked and hardenable by heat treatment aluminum alloys does not exceed 70 % of that of the base metal [1, 2] in most cases. Besides, many aluminum alloys are tend to formation of hot cracks in the weld or its fusion zone (FZ) with the base metal in the process of melt crystallization. Such an intergranular fracture is also conditioned by heating of metal up to the melting temperature in the welding zone and occurs in the places of precipitation of low-melting secondary phases [3]. Introduction of filler metal of a specific chemical composition in the weld allows increasing welded joint resistance to hot cracks formation and providing the necessary level of their strength [4].

The necessity to weld dissimilar aluminum alloys arises, however, during development of recent high-efficiency, multifunctional and economy structures in which specific advantages of each material are rationally used. It is natural that a system of metal alloying in the melt becomes significantly complicated during joining of such alloys by fusion welding that develops additional difficulties for selection of composition of the filler wire. The letter, mixing with alloys being welded, promotes obtaining of the weld metal composition providing minimum susceptibility of joints to hot cracking and high level of their mechanical properties [5, 6]. Therefore, if heating of a joint zone up to solidus temperature to be eliminated from a technological process of welding of aluminum alloys, then the conditions can be removed resulting in occurrence of crystallization cracks in the welds, and their strength characteristics are increased.

Friction stir welding (FSW) is an effective method for obtaining solid phase permanent joints without melting of the base metal. A weld in this method of welding is formed as a result of movement in limited area of small amount of plasticized metal heated due to friction to the temperature not higher 75 % of alloy melting temperature [7, 8].

The aim of the present paper is to evaluate degree of weakening, peculiarities of structure and level of strength of FS- and automatic TIG-welded joints on dissimilar thin sheet aluminum alloy.

High-strength aluminum alloys AMg6 (Al–Mg–Mn) and 1201 (Al–Cu–Mn) as well as lithium-containing alloys 1420 (Al–Mg–Li) and 1460 (Al–Cu–Li), having increased specific strength, and widely applied in manufacture of elements of aircrafts, were used in the investigations. 1.8 mm thick sheets were TIG-welded with 20 m/h speed on MW-450 unit («Fronius», Austria) at 130–150 A current applying SvAMg6, SvAMg63 and Sv1201 filler wires. FSW was carried out on a laboratory unit designed in the E.O. Paton Electric Welding Institute. Special tool with conical pin and 12 mm diameter shoulder was used for obtaining butt joints. Speed of the tool made 1420 rpm and linear speed of its movement along the butt was 8–14 m/h.

Samples for investigation of structure, determination of hardness and tensile strength at uniaxial tension were manufactured from obtained welded joints. TIG-welded standard samples were tested with the beads taken flush with the base metal as well as with additionally cleaned reinforcements.

The tests were carried out with the help of universal multipurpose servohydraulic system MTS 810. MIM-8M light microscope was used for investigation of structure of metal of welded joints. Transverse cross-sections of the welded joints were preliminary treated by means of the electrolytic polishing and additional etching in a solution of chloric, nitric and hydrofluoric acids.

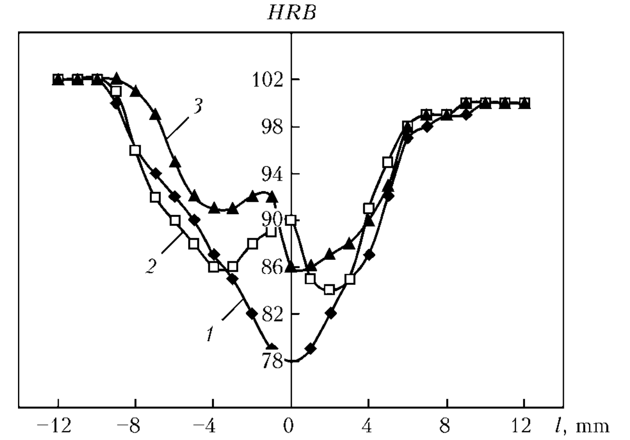

Figure 1. Distribution of metal hardness for TIG-welded joints on dissimilar aluminum alloys 1420 and 1201 made using SvAMg63 (*1*) and Sv1201 (*2*) filler wires, as well as for FS-welded joints (*3*): *l* — distance from weld axis

Hardness of metal of welded joints was measured on a weld face preliminary cleaning the reinforcement and bead flush with the base metal. At that, width of TIG-welds made on average 6.5 mm and for FS-welds it was 3.5 mm at 11 mm width of thermomechanical-affected zone (TMAZ). The degree of metal weakening in the welding zone was evaluated on the results of measuring of its hardness on ROSKWELL device under load P = 600 N.

Analysis of a hardness distribution showed that the degree of metal weakening in the weld as well as in the areas adjacent to it is always lower in FSW than in TIG welding. Thus, minimum hardness of the weld metal makes *HRB* 80 in TIG welding of 1201 alloy to AMg6 alloy using SvAMg6 filler wire and *HRB* 83 using Sv1201 filler wire. FSW method allows increasing this index up to *HRB* 86. The metal of fusion-welded weld made using SvAMg63 and Sv1201 filler wires has minimum hardness *HRB* 78 and 84, respectively, in welding together hardenable by heat treatment alloys 1420 and 1201. Application of FSW method provides weld metal hardness up to *HRB* 86 (Figure 1). Minimum hardness of the metal of TIG-welds on dissimilar alloys AMg6M and 1460 using SvAMg6 filler wire is also at the level of *HRB* 78.

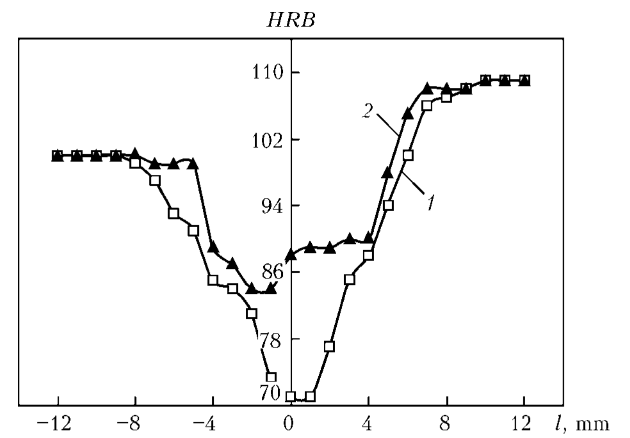

Figure 2. Distribution of metal hardness for TIG-welded joints on dissimilar copper-containing aluminum alloys 1201 and 1460 made using Sv1201 (*1*) filler wire, as well as for FS-welded joints (*2*)

Usage of Sv1201 filler wire allows increasing hardness of the weld metal up to *HRB* 84, but in this case it is significantly lower that in solid phase welding (*HRB* 89). In TIG joining of lithium-containing aluminum alloys 1420 and 1460 using SvAMg63 and Sv1201 filler wires the minimum hardness of metal in the weld is provided around *HRB* 78 and 86, respectively. This index during their solid phase welding makes not lower than *HRB* 87. TIG-welds on dissimilar hardenable by heat treatment copper-containing aluminum alloys 1201 and 1460 made using Sv1201 filler wire have minimum hardness *HRB* 71. It increases up to *HRB* 88 (Figure 2) in FSW.

Measuring of the temperature near the edge of tool shoulder, carried out with the help of chromel-alumel thermocouples, showed that lower degree of metal weakening of dissimilar aluminum alloys in FSW is conditioned by smaller heating of metal in the welding zone. Thus, the maximum temperature near the edge of shoulder makes 395 or 415 °C (Figure 3) and the metal heats up to 500 °C in a weld nugget depending on location of alloys 1460 and 1201 from the side of advancing or retreating of the tool.

Special thermomechanical conditions of joints generation in FSW promote formation of fine-grained crystalline structure of the weld metal and areas adjacent to it. The character areas — weld nugget, TMAZ and HAZ — can be outlined in the welded joints as in welding of similar aluminum alloys. But if the adjacent areas have virtually no differences in their structure from obtained in welding of corresponding alloys in similar combination, then the weld nugget contains microareas with completely and par-

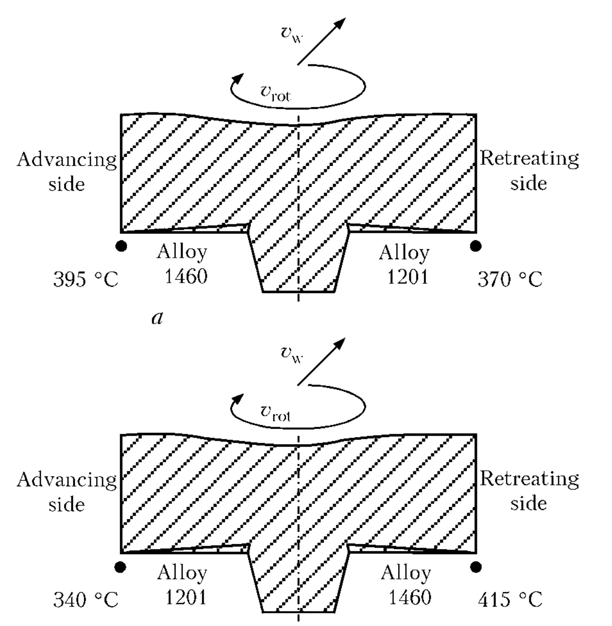

Figure 3. Dependence of maximum metal temperature near the edge of tool shoulder in FSW of dissimilar aluminum alloys 1460 and 1201 on their location relative to direction of tool rotation: *a* — alloy 1460 from the side of tool advancing, alloy 1201 from the side of retreating; *b* — conversely; v_w — welding speed; v_{rot} — speed of tool rotation

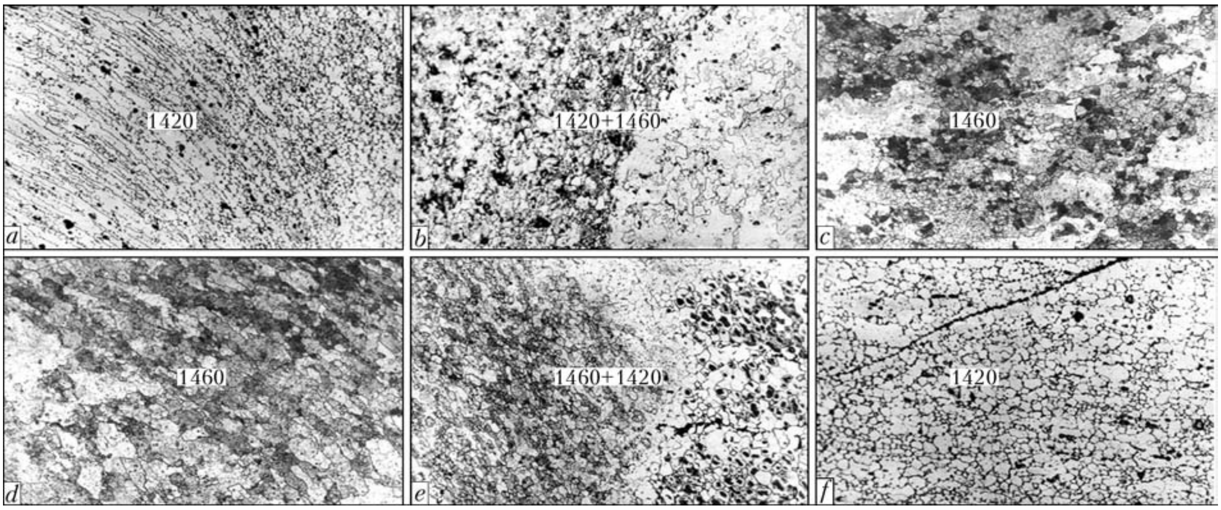

Figure 4. Microstructures (×400) of FS-welded joints on dissimilar aluminum alloys 1420 and 1460 at their different location relative to direction of tool rotation: *a, d* — TMAZ from the side of tool advancing; *b, e* — weld nugget; *c, f* — TMAZ from the side of tool retreating

tially mixed metal and microlayers with non-mixed metal (Figure 4). The lines of intermetallics and grains are oriented in parallel to sheet surface in HAZ metal and in the direction of the tool movement and plasticized metal traveling behind it in TMAZ metal. In this case, the grains are sufficiently coarse and elongated, however, they can be fine and equiaxial, apparently, recrystallized at increased temperature in a process of deformation, immediately on the weld boundary. Presence of equiaxial grains and chaotically distributed ground intermetallic inclusions is character for the weld metal. Their size is significantly smaller than in the base metal, TMAZ and HAZ metal as well as in any area of TIG-welded joint (Figure 5).

A permanent joint is formed in the solid phase without material melting during FSW process. Formed at that fine structure of the weld metal and areas immediately adjacent to it provides high strength of such joints. Thus, an ultimate strength of the samples, failing along the weld to base metal FZ from the side of 1201 alloy, is at the level of 304 MPa (Table) in alloy 1201 to alloy AMg6 welding. This index, respectively, makes 16 and 25 MPa below for TIG-welded samples with eliminated weld reinforcement made using Sv1201 and SvAMg6 filler wires. Samples of FS-welded joints on hardenable by heat treatment alloys 1201 and 1420 also failure along the weld to base metal FZ from the side of 1201 alloy. Their strength reaches 311 MPa and exceeds the results, obtained in fusion welding using filler wire SvAMg63 and Sv1201 by 39 and 71 MPa, respectively. The failure of FS-welded joint samples of AMg6 and 1460 alloys can take place along the TMAZ and HAZ from the side of AMg6 alloy. Their tensile strength is at the level of 329 MPa that exceeds this index for the samples of TIG-welded joints without weld reinforcement, made using SvAMg6 and Sv1201 filler wires, by 78 and 46 MPa, respectively. FS-welded joints of magnesium-doped alloys 1420 and AMg6 failure along the HAZ from the side of AMg6 alloy and have tensile

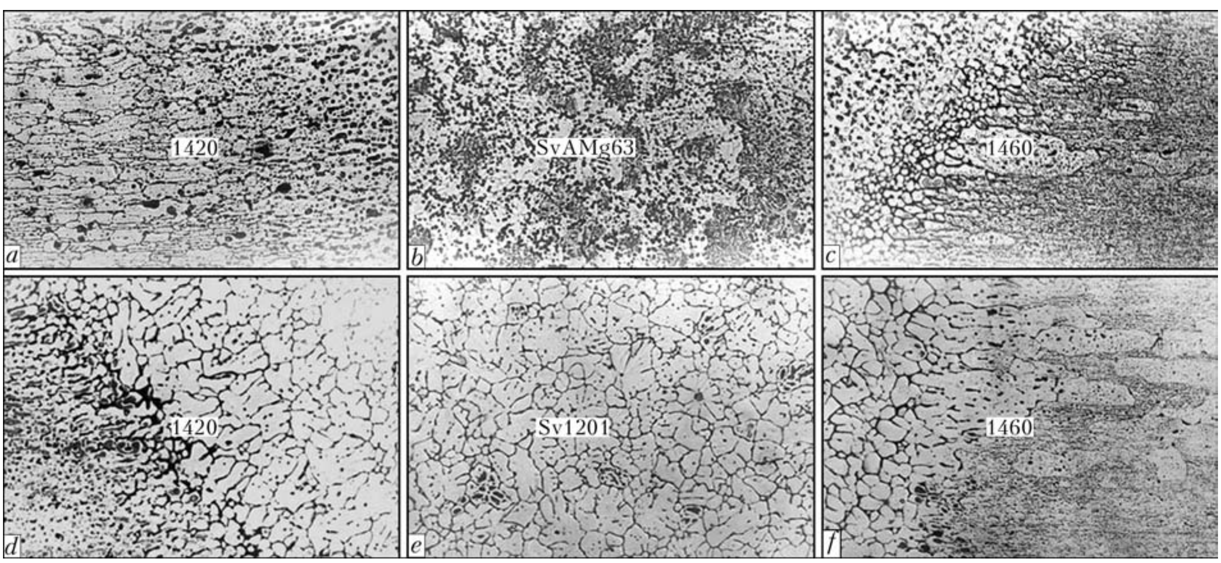

Figure 5. Microstructures (×400) of areas of joints on aluminum alloys 1420 and 1460, TIG-welded with filler wires: *a, c, d, f* — weld to base metal FZ; *b, e* — weld

Strength of FS- and TIG-welded joints on dissimilar aluminum alloys

Alloys being welded	Welding method	Filler wire	σ_t of the samples without weld reinforcement, MPa	Place of failure	σ_t of the samples with weld reinforcement, MPa	Place of failure
1201 + AMg6	FSW	–	304	FZ_{1201}	–	–
	TIG	Sv1201	288	FZ_{1201}	302	FZ_{1201}
		SvAMg6	279	FZ_{1201}	312	FZ_{1201}
1201 + 1420	FSW	–	311	FZ_{1201}	–	–
	TIG	Sv1201	240	FZ_{1420}	287	FZ_{1201}
		SvAMg63	272	FZ_{1420}	301	FZ_{1201}
AMg6 + 1460	FSW	–	329	$TMAZ_{AMg6}$ HAZ_{AMg6}	–	–
	TIG	Sv1201	283	FZ_{AMg6}	283	FZ_{1460}
		SvAMg6	251	Weld	321	FZ_{AMg6}
1420 + AMg6	FSW	–	340	HAZ_{AMg6}	–	–
	TIG	SvAMg63	314	Weld/FZ_{AMg6}	343	FZ_{AMg6}
1201 + 1460	FSW	–	285	FZ_{1201}	–	–
	TIG	Sv1201	257	Weld	294	FZ_{1201}
1420 + 1460	FSW	–	286	FZ_{1420}	–	–
	TIG	Sv1201	281	FZ_{1420}	335	FZ_{1420}
		SvAMg63	288	Weld/FZ_{1420}	358	FZ_{1420}

Note. Average values of indices according to test results of 3–5 samples are given.

strength 340 MPa, whereas samples of TIG-welded joint without weld reinforcement have tensile strength only 314 MPa. The strength of the joint samples makes 285 MPa in FSW of copper-doped hardenable by heat treatment alloys 1201 and 1460. Their failure occurs on the weld to base metal FZ from the side of 1201 alloy as in TIG-welded samples with weld reinforcement made using Sv1201 filler wire. But joints without weld reinforcement failure along the weld metal and have strength below 275 MPa, i.e. lower than joints obtained in the solid phase. And even presence of the weld reinforcement in all samples of joints mentioned above just rarely allows achieving the same level of strength as in the solid phase welding. FS-welded joints on lithium-containing aluminum alloys 1420 and 1460 failure along the weld to base metal FZ from the side of alloy 1420 and have 286 MPa tensile strength. Approximately the same strength index is provided in the samples of joints without weld reinforcement in TIG welding using Sv1201 and SvAMg63 filler wires. However, strength of the samples with weld reinforcement made using Sv1201 and SvAMg63 wires increases up to 335 and 358 MPa, respectively.

Thus, the weld and areas adjacent to it are heated below the base metal melting temperature in FSW, due to which the possibility of formation of crystallization cracks is eliminated in obtaining of the permanent joints on single and dissimilar aluminum alloys.

Intensive mixing of plasticized metal in the limited area under excessive pressure promotes formation of subdendritic structure of the weld nugget, consisting of homogeneous and partially mixed layers of alloys being welded as well as TMAZ, containing simultaneously stretched elongated relative to the direction of tool movement grains and small recrystallized equiaxial grains.

Grain size refinement, increase of volume fraction of their boundaries and shattering of intermetallic phases in metal of FS-welded welds on dissimilar aluminum alloys allow obtaining higher values of tensile strength of welded joints than in fusion welding.

1. Lozovskaya, A.V., Chaika, A.A., Bondarev, A.A. et al. (2001) Softening of high-strength aluminium alloys in different fusion welding processes. *The Paton Welding J.*, **3**, 13–17.
2. Mashin, V.S., Poklyatsky, A.G., Fedorchuk, V.E. (2005) Mechanical properties of aluminium alloys in consumable and nonconsumable electrode arc welding. *Ibid.*, **9**, 39–45.
3. Ishchenko, A.Ya. (1985) Character of hot cracks in fusion welding of high-strength aluminium alloys. In: *Current problems of welding of nonferrous metals*. Kiev: Naukova Dumka.
4. Rabkin, D.M. (1986) *Metallurgy of fusion welding of aluminium and its alloys*. Kiev: Naukova Dumka.
5. Liptak, I.A., Baysinger, F.R. (1968) Welding dissimilar aluminium alloys. *Welding J.*, **4**, 173–180.
6. Ishchenko, A.Ya., Lozovskaya, A.V., Yavorskaya, M.R. et al. (1991) Properties of welded joints of AD0 aluminium with AMg6 alloy using different filler wires. *Avtomatich. Svarka*, **5**, 12–18.
7. Dawes, C.J., Thomas, W.M. (1996) Friction stir process welds aluminium alloys. *Welding J.*, **3**, 41–45.
8. Lambrakos, S.G., Fonda, R.W., Milewski, J.O. et al. (2003) Analysis of friction stir welds using thermocouple measurements. *Sci. and Techn. of Welding and Joining*, **5**, 385–390.
9. Lohwasser, D. (2001) Welding of airframes by friction stir. In: *Proc. of 3rd Int. Symp. on Friction Stir Welding* (Kobe, Japan, Sept. 27–28, 2001), 1–6.
10. Polovtsev, V.A., Makarov, N.V., Shillo, G.V. et al. (2008) Friction welding of aliminium liners of metal-composite high-pressure cylinders. *Tekhnologiya Mashinostroeniya*, **1**, 38–41.