https://doi.org/10.37434/tpwj2020.02.09

INFLUENCE OF SCANDIUM ON MECHANICAL PROPERTIES OF WELDED JOINTS OF D16 ALLOY PRODUCED USING FILLER WIRES OF DIFFERENT ALLOYING SYSTEMS

A.G. Poklyatsky[1], **V.E. Fedorchuk**[1], **S.l. Motrunich**[1], **Yu.V. Falchenko**[1] and **G.P. Kisla**[2]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»
37 Peremohy Prosp., 03056, Kyiv, Ukraine

The impact of scandium in filler wires of SvAMg6, Sv1201 and SvAK5 type, as well as arc oscillations, caused by electric current passage through the filler section, on weld structure formation was studied in nonconsumable electrode argon-arc welding of sheet aluminium alloy D16. Curves of metal hardness distribution in the welding zone are shown and strength limits of welded joints and weld metal after natural ageing of the specimens are determined. It is shown that use of scandium filler wires, similar to standard batch-produced ones, leads to formation of a fine-grained dendritic structure of weld metal. However, the subdendritic structure does not form even in welding with arc oscillations, because of a low (0.15–0.17 %) scandium content in welds. Use of scandium-containing filler wires can lower the degree of weld metal softening at lowering of the total content of the main alloying elements in them. Positive impact of scandium additives together with application of arc oscillations on the degree of softening and ultimate strength of weld metal is noticeable at application of filler wire of Al-Si alloying system. However, the maximum level of strength, both of the welded joints and the weld metal, is provided in nonconsumable electrode argon-arc welding of D16 alloy 2 mm thick using batch-produced filler wires SvAMg6 and SvAMg63. 21 Ref., 2 Tables, 3 Figures.

Keywords: D16 aluminium alloy, nonconsumable electrode argon-arc welding with arc oscillations, scandium, microstructure, hardness, ultimate strength

Aluminum alloys of different alloying systems are widely used for manufacture of space and aircraft equipment, sea and river vessels, railway and automobile transport and other structures of critical purpose [1−3]. This is largely predetermined by their high structural strength, which is provided by the optimal combination of strength characteristics, which determines the material intensity of structures and resistance to cracking, which indicates their resistance to brittle fracture and providing the reliability and life of units during their operation [4]. To produce permanent joints from the semi-finished products of these alloys in most cases, nonconsumable (tungsten) electrode argon-arc welding (NEAAW) is used, in which the weld formation occurs as a result of melting welded edges and filler wire and their subsequent crystallization [5]. At this time, the weld metal has a cast, mostly large crystalline structure with a clearly pronounced orientation of dendrites, as a result of which, its tensile strength for the most thermally hardened alloys does not exceed 50−60 % of this value for the base material [6].

Therefore, in order to increase the strength of welds, during the process of welding it is necessary to create favorable conditions for the formation of a fine-grained disoriented structure of metal in them. Among the known widely applied methods of influence on the processes of weld pool metal crystallization, the use of welding wires modified with zirconium, acting as forced crystallization centers, is of particular importance. In addition, the effectiveness of using scandium as a modifier has been long investigated, the unique influence of which is predetermined by the dimensional and structural similarity of crystalline lattices of aluminum (0.4405 nm) and $A1_3Sc$ phase (0.4407 nm), due to which the particles of the latter act as nuclei of crystallization centers in the welds [7−9]. As a result, the formation of fine-crystalline structure of welds is provided, which has a positive effect on their physical and mechanical properties [10].

A.G. Poklyatsky — https://orcid.org/0000-0002-4101-2206, V.E. Fedorchuk — https://orcid.org/0000-0002-9929-3231, S.l. Motrunich — https://orcid.org/0000-0002-8841-8609, Yu.V. Falchenko — https://orcid.org/0000-0002-3028-2964, G.P. Kisla — https://orcid.org/0000-0003-0791-6903

Thus, during welding of deformed thermally non-strengthened alloys of the Al–Mg alloying system due to the use of scandium alloyed wires, the dispersion hardening and structural hardening of weld metal occurs, which provides an increase in their tensile and yield strength [6, 11]. The introduction of scandium into the filler wires has a positive effect also during welding of thermally hardened aluminum alloys of the Al-Mg-Li alloying system. In addition, in order to increase the tensile strength of welds immediately after welding during heat treatment of welded joints, favorable conditions are created for their further strengthening by isolating not only strengthening particles of basic alloying elements, but also dispersed aluminum-scandium phases [6, 12, 13].

Regarding aluminum alloys doped with copper, the introduction of scandium may reveal in different way. Sometimes scandium with copper can form a chemical compound (W-phase), as a result of which its impact on refining the weld metal structure and its strengthening will be reduced [14]. In addition, an increase in the volume fraction of excess phases can lead to a decrease in the strength, ductility and fracture toughness of weld metal [15]. However, the experimental investigations carried out on alloys 1201 and 1460 indicate an increase in the tensile strength of the welds produced by NEAAW using the filler wire of type Sv1201 with 0.5 % of Sc [6]. Also a positive effect of scandium on physicomechanical characteristics of semi-finished products and welded joints of alloys of the Al−Zn−Mg−Cu alloying system is observed [6, 16].

The sharp oscillations in the melt of the welding pool caused by periodic change in the power influence of the arc as a result of pulsations of welding current or deviation from the vertical position [17, 18] can be the other effective way of changing conditions of metal crystallization during the welding process. As a result of such oscillations, periodic melting of second-order axes of the formed crystals occurs and the activity of the crystallization centers increases due to the periodic change of the metal temperature at the crystallization front. This leads to violation of crystallization continuity and formation of long oriented crystals and facilitates the formation of a fine-grained disoriented structure of the weld metal [19].

During welding thin-sheet (<3 mm) semi-finished products, when the volume of filler wire in a weld is small (<20 %), it is not possible to achieve the optimum (0.3−0.4 % [20]) concentration of scandium in the weld metal, at which the formation of subdendritic structure of weld metal is provided. Therefore, in such cases it is advisable to perform arc welding with oscillations of the weld pool melt simultaneously with the use of scandium-modified filler wires to guarantee producing a disoriented fine-grained dendritic structure over the entire volume of the weld metal [21].

The aim of the investigations is to evaluate the influence of scandium in the filler wires of the Al−Mg, Al−Cu and Al−Si alloying systems and arc oscillations caused by passing electric current through the area of filler on the formation of weld structure, softening of metal and tensile strength of welded joints and weld metal in NEAAW of thin-sheet D16 alloy.

Procedure of investigations. Automated NEAAW of butt joints of 2 mm thick sheets of aluminum D16 alloy (wt.%: 4.5 Cu; 1.7 Mg; 0.53 Mn; 0.19 Si; 0.21 Fe; 0.11 Zr; 0.06 Ti; the remnant is Al) was performed on an alternating current with a rectangular wave shape of 200 Hz with the use of the welding head ASTV-2m from the power source MW-450 (Fronius, Austria). The welding speed was 20 m/h, the value of welding current was 170 A and the feed speed of the 1.6 mm diameter filler wire was 82 m/h. During welding, the serial filler wires of three alloying systems were used: Al−Mg (SvAMg6), Al−Cu (Sv1201) and Al−Si (SvAK5), as well as the wires similar to them modified with zirconium and scandium — SvAMg63 (Al−6.2 % Mg−0.6 % Mn−0.2 % Zr), Sv1571 (Al−6.1 % Mg−0.19 % Mn−0.06 % Zr−0.015 % Ti−0.52 % Sc), Sv1201Sc (A1−6 % Cu−0.1 % Ti−0.2 % Zr−0.5 % Sc) and SvAK5Sc (A1−5 % Si−0.5 % Sc). In addition, to form a homogeneous fine-grained disoriented metal structure over the entire volume of welds the welding was performed with oscillations in the molten metal of the weld pool, caused by deviations of the arc from its vertical position due to passing of a constant («+» — to earth) current of the value of 200 A through the area of the 25 mm long filler wire directly before it gets into the welding pool [18, 21].

Before welding, chemical etching of sheets was carried out according to a generally-accepted technology and mechanical cleaning of surfaces and ends of welded edges to a depth of approximately 0.1 mm. The sheets of the alloy in the state after quenching and natural aging (tensile strength is σ_t = 445 MPa, elongation is δ = 11 %) were welded between each other along the direction of their rolling. All the investigations and tests of the specimens of welded joints were performed within 10−12 months after their welding, when their natural aging process took place.

The hardness of the metal in different zones of welded joints was measured on the facial surfaces of the specimens of the produced joints after cleaning the reinforcement and penetration of the welds flush with the base material in the Rockwell device at a load P = 600 N. The evaluation of structural features of welded joints was carried out with the use of the optical electron microscope MMT-1600V. The tensile strength of welded joints (σ_t^{wj}) was determined at a static tension of standard flat specimens with a width of a working part of 15 mm with a cleaned weld penetration in the standard servo-hydraulic complex MTS 318.25, and the tensile strength of the weld metal (σ_t^{wm}) was determined on the same specimens with the cleaned reinforcement and weld penetration.

The analysis of chemical composition of the specimens was performed in the X-ray fluorescence analyzer EXPERT3L. The chemical analysis was based on the energy-dispersive X-ray fluorescence elemental analysis according to the method of fundamental parameters with excitation of characteristic radiation of atoms of the specimen by photons of a braking spectrum of a low-power X-ray tube and recording this radiation by means of a semiconductor detector with a thermal electric cooling.

Results of investigations and their discussion. According to the results of the carried out investigations, it was established that during a conventional NEAAW of 2 mm thick D16 alloy with a serial filler wire SvAMg6, the hardness of metal in the central part of the weld is at the level of *HRB* 92.5–93.0, and in the zone of its fusion with the base material is *HRB* 97.0–97.5 (Figure 1). The use of the filler wire SvAMg63 containing zirconium as a modifier almost does not change the nature of hardness distribution of the metal in the welding zone even in NEAAW with arc oscillations caused by passing of electric current through the filler area. And, accordingly, the tensile strength of welded joints and the tensile strength of the weld metal at a static tension of the specimens produced with the filler wires SvAMg6 and SvAMg63 are

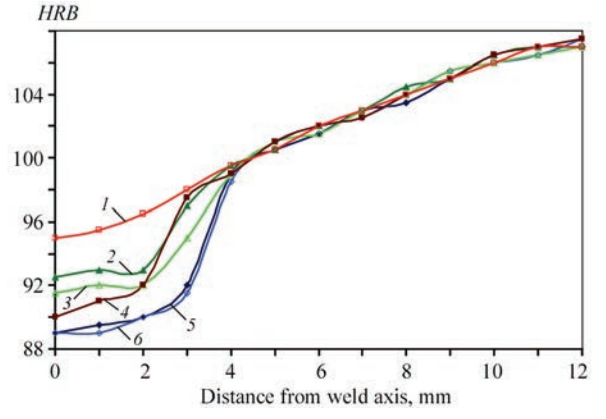

Figure 1. Distribution of hardness in butt joints of 2 mm thick D16 alloy after welding and their natural aging, produced by NEAAW using filler wires of different alloying systems and arc oscillations: *1* — SvAK5Sc with arc oscillations; *2* — SvAMg6; *3* — Sv1571 with arc oscillations; *4* — SvAK5; 5 – Sv1201; *6* — Sv1201Sc with arc oscillations

approximately at the same level (Table 1). The use of the filler wire of type Sv1571, containing 0.52 % of Sc leads to a slight decrease in the hardness of the metal in the area of forming a permanent joint. Thus, in the weld produced by NEAAW with the specified wire and arc oscillations, the hardness of the metal is *HRB* 91.5–92.0 and in the fusion zone with the base material it is *HRB* 95.0–95.5. Moreover, the tensile strength of welded joints and the tensile strength of weld metal are slightly reduced to 336 and 320 MPa, respectively. The fracture of all specimens with a cleaned weld penetration produced with the investigated filler wires of the alloying system Al–Mg at a static tension occurred in the zone of fusion of the weld with the base material, and of the specimens with cleaned reinforcement and weld penetration — in the central part of the weld (Figure 2).

Table 1. Tensile strength of welded joints of 2 mm thick D16 alloy after their natural aging, produced by NEAAW using different filler wires

Type NEAAW	Filler wire	Tensile strength, MPa	
		$\sigma_t^{w.j}$	$\sigma_t^{w.m}$
Natural	SvAMg6	369–352 / 363	345–325 / 335
With arc oscillations	SvAMg63	364–340 / 359	339–321 / 332
	Sv1571	343–332 / 336	330–311 / 320
Natural	Sv1201	360–340 / 349	318–312 / 315
With arc oscillations	Sv1201Sc	363–341 / 350	319–311 / 315
Natural	SvAK5	347–339 / 342	260–255 / 257
With arc oscillations	SvAK5Sc	362–343 / 350	318–308 / 312

Note. In the numerator the maximum and minimum and in the denominator — the average values of the results of the test of 4–6 specimens are given.

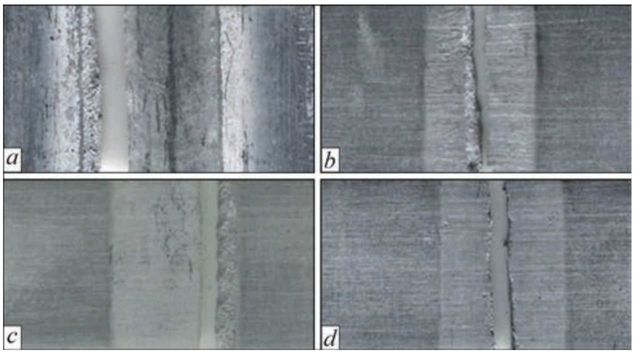

Figure 2. Appearance of working part of specimens with cleaned weld penetration (*a*) and cleaned weld reinforcement and penetration (*b*–*d*) of 2 mm thick D16 alloy after their fracture during tests produced by NEAAW using filler wires of different alloying systems: *a* — Al–Mg, Al–Cu or Al–Si; *b* — Al–Mg; *c* — Al–Cu; *c* — Al–Si

According to the results of the carried out investigations of microstructure of the specimens of the produced welded joints, it was established that, regardless of the chemical composition of filler wires and presence of scandium in them, a fine-grained dendritic structure of metal is formed in the welds (Figure 3), although dendritic parameter for weld metal can vary during welding using different filler wires. Thus, when using the wire SvAMg6 it amounts to 9.95 μm, when using the wire SvAMg63 — 10.20 μm, and the wire Sv1571 — 12.36 μm. The carried out analysis of chemical composition of the welds showed that when using the filler wire Sv1571, the content of scandium in them is at the level of 0.17 % (Table 2). Of course, such amount of scandium is not sufficient to form the primary particles of scandium aluminide in the weld metal. Therefore, the use of this filler wire even in NEAAW with arc oscillations cannot provide the necessary conditions for the formation of a subdendritic structure in the weld metal, due to which the tensile strength of the welds significantly increases. In addition, the results of the analysis of chemical composition of the welds indicate that when using these wires, the total amount of the main alloying elements in the metal of the welds, on which the tensile strength of

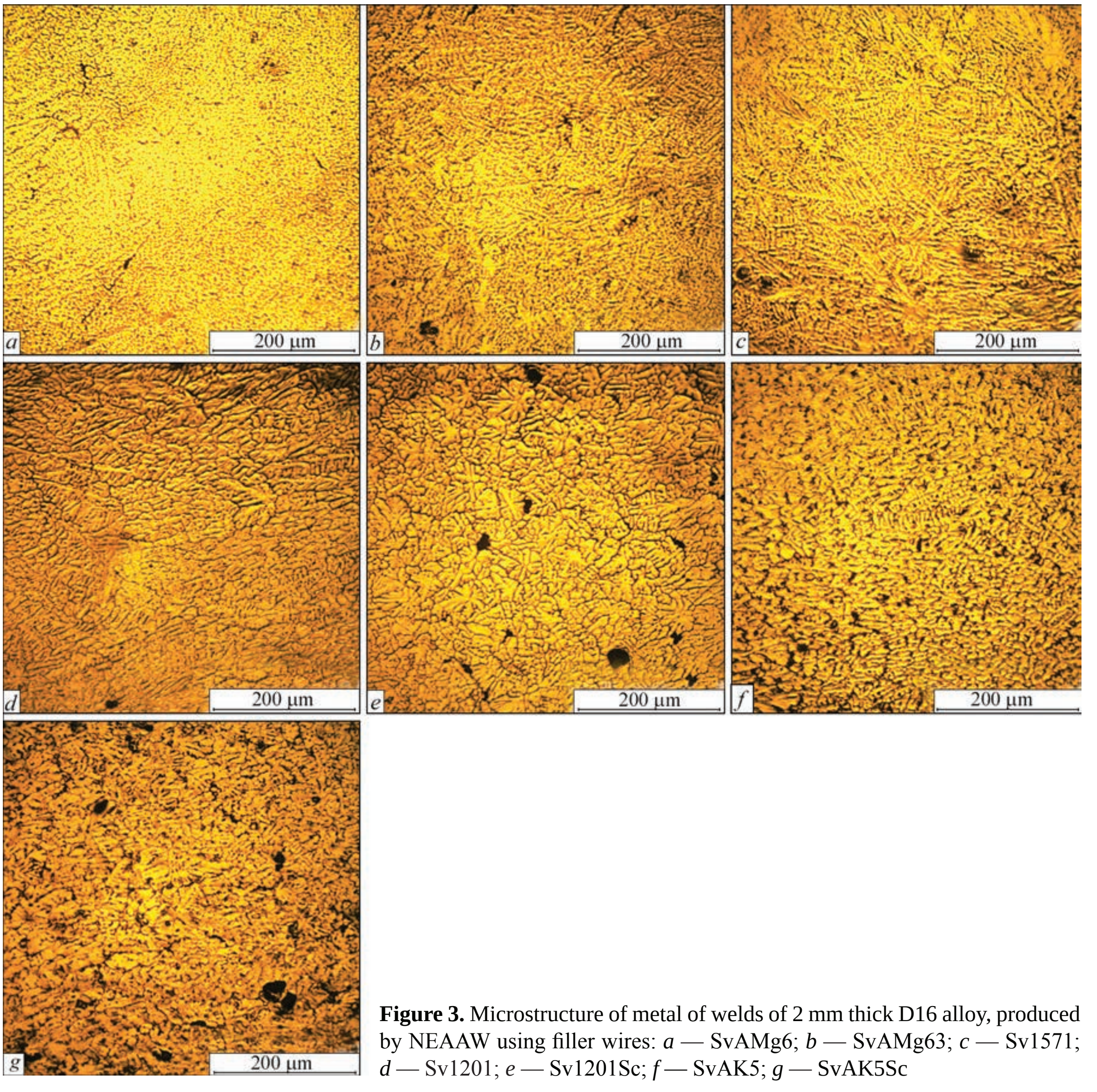

Figure 3. Microstructure of metal of welds of 2 mm thick D16 alloy, produced by NEAAW using filler wires: *a* — SvAMg6; *b* — SvAMg63; *c* — Sv1571; *d* — Sv1201; *e* — Sv1201Sc; *f* — SvAK5; *g* — SvAK5Sc

Table 2. Content of main alloying elements and modifiers in the metal of welds of 2 mm thick D16 alloy, produced by NEAAW with the use of different filler wires

Filler wire	Alloying elements, wt.%				Modifiers, wt.%	
	Mg	Cu	Si	$\Sigma_{Mg+Cu+Si}$	Zr	Sc
SvAMg6	3.22	2.79	–	6.01	–	–
SvAMg63	2.92	2.91	–	5.83	0.10	–
Sv1571	2.61	3.00	–	5.61	0.05	0.17
Sv1201	1.08	5.91	–	6.99	0.07	–
Sv1201Sc	0.86	5.70	–	6.56	0.06	0.15
SvAK5	1.02	2.63	1.99	5.64	–	–
SvAK5Sc	1.06	2.87	1.78	5.71	0.06	0.15

the latter depends, is different: for SvAMg6 it is the highest, and for Sv1571 it is the lowest.

In NEAAW of D16 alloy using the filler wires Sv1201 and Sv1201Sc by the alloying system Al–Cu, the metal hardness in the zone of forming permanent joints is at the same level — *HRB* 89.0–90.0 in the weld metal and *HRB* 91.5–92.5 in the zone of their fusion with the base material. Of course, this provides the same values of the tensile strength of welded joints (350 MPa) and the tensile strength of weld metal (315 MPa) at a static tension of the specimens produced using such filler wires. The fracture of the specimens with a cleaned weld penetration occurs along the fusion zone with the base material, and of the specimens with the cleaned reinforcement and weld penetration – along the weld metal closer to this fusion zone.

The examinations of microstructure of metal in the welds produced in NEAAW using both filler wires of the alloying system Al–Cu made it possible to establish that dendritic parameter is the same for them and amounts to 12.36 μm. But when using a scandium filler wire, the total amount of the main alloying elements in the weld metal is slightly lower than in that produced using a serial filler wire. Obviously, it is precisely due to the presence of scandium in the welds and application of arc oscillations during their welding and it is possible to provide the same values of dendritic parameter and the tensile strength of welds, as in conventional NEAAW of D16 alloy using the serial filler wire Sv1201.

The positive effect of scandium additives, together with the use of NEAAW with arc oscillations, can be observed in the use of the filler wire of the alloying system Al-Si. Thus, during a conventional NEAAW of D16 alloy using the filler wire SvAK5, the hardness of the metal in the central part of the weld is at the level of *HRB* 90.0–92.0, and in the zone of its fusion with the base material is at the level of *HRB* 97.5–98.0. The use of scandium-modified filler wire SvAK5Sc in NEAAW with arc oscillations provides an increase in the hardness of the metal in the weld to *HRB* 95.0–96.5, and in the zone of its fusion with the base material — to *HRB* 98.0–99.0. Accordingly, the tensile strength of weld metal produced using scandium filler wire is 55 MPa higher than this value for the joints produced using the serial filler wire SvAK5 and is at the level of 312 MPa. Moreover, the presence of scandium in the filler wire has a lesser effect on increasing the tensile strength of welded joints since fracture of the specimens with a cleaned weld penetration occurs in the area of fusion of the weld with the base material. And the specimens with a cleaned reinforcement and weld penetration at a static tension are fractured in the central part of the weld.

According to the result of the analysis of microstructure of the welds produced with the use of filler wires of the alloying system Al-Si, it was found that dendritic parameter for the weld metal produced using the filler wire SvAK5 was 11.66 μm and using the filler wire SvAK5Sc — 11.33 μm. In addition, the results of studying the chemical composition of the weld metal indicate a rather small increase in the total amount of the main alloying elements in them when using a scandium-containing filler wire. Therefore, the presence of scandium in the filler wire of the alloying system Al-Si together with arc oscillations during NEAAW of D16 alloy contribute to the refinement of the dendritic structure of the weld metal and increase in their tensile strength.

Conclusions

1. During nonconsumable electrode argon-arc welding of 2 mm thick aluminum D16 alloy with the investigated filler wires of the alloying systems Al–Mg, Al–Cu and Al–Si regardless of the presence of scandium in them, in the welds a fine-grained dendritic structure is formed. In addition, dendritic parameter for the weld metal can vary when using filler wires of different chemical composition.

2. The presence of scandium in the filler wire of the alloying system Al–Si together with arc oscillations during welding of this alloy by a nonconsumable electrode contribute to the refinement of dendritic structure of the weld metal and increase in their hardness and tensile strength.

3. The maximum level of strength of welded joints and weld metal is provided by nonconsumable elec-

trode argon-arc welding of 2 mm thick aluminum D16 alloy with serial filler wires SvAMg6 and SvAMg63.

4. The use of filler wires of the alloying systems Al–Mg and Al–Cu with scandium in nonconsumable electrode argon-arc welding of 2 mm thick aluminum D16 alloy with arc oscillations does not allow providing the formation of subdendritic structure of metal in welds and thus significantly increasing their strength and can only slightly reduce the degree of softening the weld metal while reducing the total amount of the main alloying elements.

1. Ishchenko, A.Ya., Labur, T.M., Bernadsky, V.N., Makovatskaya, O.K. (2006) *Aluminium and its alloys in modern welded structures*. Kiev, Ekotekhnologiya [in Russian].
2. Beletsky, V.M., Krivov, G.A. (2005) *Aluminium alloys (composition, properties, technology, application)*: Refer. Book. Ed. by I.N. Fridlyander. Kiev, KOMINTEX [in Russian].
3. Kablov, E.N. (2000) Main directions of development of materials for aerospace engineering of 21st century. *Perspektivnye Materialy*, **3**, 27–36 [in Russian].
4. Ostash, O.P. (2015) *Fracture mechanics and strength of materials*: Refer. Book. Vol. 15. Structure of materials and fatigue life of structure components. Ed. by V.V. Panasyuk, Lviv, SPOLOM [in Ukrainian].
5. Ishchenko, A.Ya., Labur, T.M. (2013) *Welding of modern structures from aluminium alloys*. Kiev, NPP NANU [in Russian].
6. Mashin, V.S., Poklyatsky, A.G., Fedorchuk, V.E. (2005) Mechanical properties of aluminium alloys in consumable and nonconsumable electrode arc welding. *The Paton Welding J.*, **9**, 39–45.
7. Davydov, V.G., Elagin, V.I., Zakharov, V.V., Rostova, T.D. (1996) On alloying of aluminium alloys with scandium and zirconium additives. *Metallovedenie i Termich. Obrab. Metallov*, **8**, 25–30 [in Russian].
8. Bondarev, B.I., Elagin, V.I. (1992) New aluminium alloys with scandium. *Tekhnologiya Lyogkikh Splavov*, **5**, 22–28 [in Russian].
9. Ishchenko, A.Ya. (2003) *Aluminium high-strength alloys for welded structures*. *Advanced materials and technologies*. Vol. 1, Kyiv, Akademperiodika, 50–82 [in Russian].
10. Milman, Yu.V. (2003) Effect of scandium on structure, mechanical properties and corrosion resistance of aluminium alloys. *Ibid*., 335–360 [in Russian].
11. Ryazantsev, V.I., Filatov, Yu.A. (2003) Technological aspects of arc welding of aluminium alloys with scandium. *Aviats. Promyshlennost*, **1**, 13–17 [in Russian].
12. Turkina, N.I., Semenova, B.V. (1992) Structure and properties of Al–Mg–Li system alloys with scandium. *Tekhnologiya Lyogkikh Splavov*, **1**, 57–59 [in Russian].
13. Bratukhin, A.G., Tretyak, N.G., Sklabinskaya, I.E. (1993) Structure and mechanical properties of welded joints of aluminium-lithium alloys in welding with scandium-containing test additives. *Ibid*., **12**, 11–15 [in Russian].
14. Zakharov, V.V., Rostova, T.D. (1995) Alloying with scandium of aluminium copper-containing alloys. *Metallovedenie i Termich. Obrab. Metallov*, **2**, 23–27 [in Russian].
15. Elagin, V.I., Zakharov, V.V., Rostova, T.D., Filatov, Yu.A. (1989) Some physical metallurgy principles of alloying, production technology and heat treatment of aluminium scandium-containing alloys. *Tekhnologiya Lyogkikh Splavov*, **9**, 27–34 [in Russian].
16. Fridlyander, I.N., Senatorova, O.G., Novikov, I.I. et al. (1993) Superplasticity of high-strength alloys of Al–Zn–Mg–Cu system alloyed with scandium. *Ibid*., **7–8**, 43–47 [in Russian].
17. Brodyagina, I.V. (1998) Arc welding of aluminium alloys using magnetic fields. *Svarochn. Proizvodstvo*, **9**, 48–51 [in Russian].
18. Poklyatsky, A.G., Ishchenko, A.Ya., Grinyuk, A.A. et al. (2002) Consumable-electrode argon-arc welding of aluminium alloys with arc oscillations. *The Paton Welding J.*, **2**, 18–22.
19. Ishchenko, A.Ya., Poklyatsky, A.G., Lozovskaya, A.V. et al. (1990) Influence of low-frequency modulation parameters of rectangular-shaped heteropolar current on weld structure in welding of aluminium alloys. *Avtomatich. Svarka*, **9**, 23–27 [in Russian].
20. Fedorchuk, V.E., Kushnaryova, O.S., Alekseenko, T.A., Falchenko, Yu.V. (2014) Peculiarities of alloying of weld metal of high-strength aluminium alloy welded joints with scandium. *The Paton Welding J.*, **5**, 28–32.
21. Poklyatsky, A.G., Motrunich, S.I. (2019) Strength of welded joints of heat-hardenable aluminium alloys in TIG and friction stir welding. *Ibid*., **2**, 13–18.

Received 23.12.2019

FEBRUARY 20, 1986 On February 20, 1986 the Soviet Union launched the scientific orbital station «Mir», replacing the orbital stations «Salyut» and became for about 15 years a single in the world manned space laboratory for long-term scientific-technical experiments and investigation of human body in space. Further on the solar-cell batteries designed at the E.O. Paton Electric Welding Institute were deployed at the station.

FEBRUARY 26, 1934 The first plant for the production of the «people's» car Volkswagen was opened. The first produced car was the famous VW Beetle. This is the most popular car in history, produced without additional consideration of the basic design. In total, 21,529,464 cars were manufactured. In its development Ferdinand Porsche (later founder of the second variant of the Tiger tank) was involved, who was keeping contact with Ford and other pioneers and actively introduced new technologies at the plant. Welding provided reliability and quick assembly of the car in the conveyor.