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CONSUMABLE ELECTRODE WELDING OF D16 ALUMINIUM ALLOY WITH WELD METAL MICROALLOYING

T.M. Labur, V.A. Koval, M.R. Yavorska

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The paper gives the results of investigation of the influence of application of two isolated filler wires or embedded elements of different chemical composition on the features of formation of D16 aluminium alloy welds in consumable electrode welding. Wires of Zv1201, ZvAK5, ZvAK12 grades of 1.6 mm diameter and embedded elements cut out of V92, V96 and 7056 alloy blanks with different content of zinc were evaluated. It is shown that ZvAK5 wire ensures reduction of the length of solidification cracks and number of pores in welded joints, and welded joint strength becomes higher at addition of zinc into the weld.

KEYWORDS: aluminium alloy, arc welding, consumable electrode, welded joints, filler wires, structure, solidification cracks, mechanical properties, investigations

INTRODUCTION

At nonconsumable electrode welding of D16 alloy of Al–Cu alloying system solidification cracks are observed along the weld axis and in the zone of fusion with the base metal. The joint quality deteriorates. The causes for such a phenomenon are the dimensions of brittleness temperature range and low ductility of metal in this region, particularly, when the alloy is in T1 condition, i.e. after artificial aging [1–8]. At the same time, wide industrial application of this alloy in flying vehicle structures necessitates a more thorough study of the technological capabilities of consumable electrode welding of this alloy.

Note that the presence of some elements (iron, copper, silicon, etc.) causes a nonuniform distribution in the aluminium alloy structure, which is often found in their semifinished products, and at welding it leads to formation of low-melting eutectics in the intergranular and intercrystalline space, expands the solidification range, and this way causes higher sensitivity of the alloy to the thermal cycle of welding. Weld metal proneness to solidification crack formation becomes greater. Crack dimensions depend on thermophysical conditions of consumable or nonconsumable electrode welding, which determine the nature of primary phase precipitate distribution.

It is known [4, 9, 10] that the process of weld metal solidification is of an intermittent nature, related to an abrupt change of the solidification rate and temperature gradient. Increase of process dynamics leads to initiation of sites of transition from one kind of solidification to another one not only in the weld center, but also in the fusion zone. The main precipitation phases at process heating of the alloy are $CuAl_2$ (θ)-phase and Al_2CuMg (S)-phase. In the case of the ratio of Cu/Mg alloying elements ≤ 2.6 formation of S-phase is observed in the structure, which is necessary for D16 alloy hardening by phase formation. At the ratio of Mg/Si = 1.73 also Mg_2Si phase precipitates. Such transitions usually arise in welding alloys with relatively high content of alloying elements and admixtures. The latter, in their turn, influence the shape and dispersity of eutectic precipitates in the weld structure [1–7]. The shape and dispersity of the precipitates are due to metal pool solidification rate. In case of its increase, the process of admixtures diffusion on the interphase becomes shorter, narrowing the wall of crystallite cells. Eutectic phase precipitation occurs predominantly on the intercrystalline boundary, particularly at a low welding speed. At the specified welding mode the solidification rate varies in a wide range relative to the weld width. The nature of phase precipitates changes considerably at crystallite growth. In this case, eutectic precipitates with thinner walls of intercrystallite layers are observed in the weld center, where the solidification rate is higher, and the cell width is smaller than that at the fusion line.

The weld metal solidification process is influenced by the pattern of distribution of primary phase precipitates in the base metal and thermophysical conditions of consumable electrode welding [4–13]. The dynamic nature of the solidification process at weld pool cooling leads to formation of centers of transition from one kind of solidification to another one. Such transitions take place at welding alloys with a relatively high content of alloying elements and admixtures that affects the shape and dispersity of phase precipitates in the weld structure.

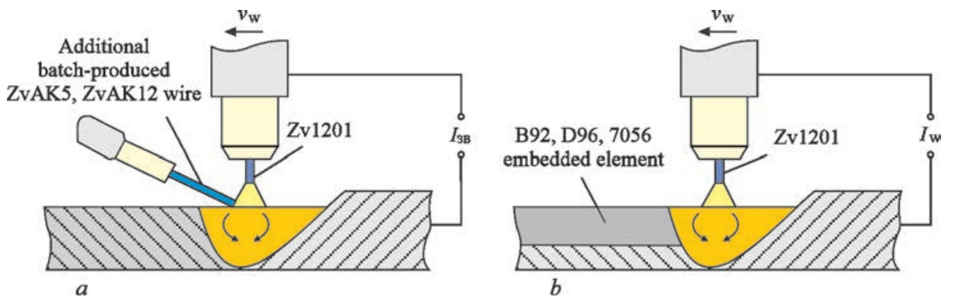

Figure 1. Technology variants of welding D16 alloy with two filler wires (*a*) and embedded elements (*b*) for weld metal alloying and improvement of the mechanical properties

OBJECTIVE OF THE STUDY AND EXPERIMENTAL PROCEDURE

One of the possible ways of improvement of structural homogeneity of welds on 6 mm D16 aluminium alloy (Table 1) can be simultaneous application of two isolated filler wires or embedded elements of different chemical composition in the weld pool. Here, conditions are in place for physicochemical interaction of alloying elements and admixtures of base metal and filler wires, which promotes formation of eutectics of a balanced composition and improves the homogeneity of the weld structure. Therefore, the objective of this work is revealing the structural features of welds produced using two filler wires or embedded elements (Figure 1). One wire of Zv1201 grade, the chemical composition of which is close to that of D16 alloy, will be fed directly into the arc burning zone, and the other — into the weld pool head part, which corresponds to the technology of nonconsumable electrode welding.

Transfer of liquid metal drops to the common pool will form the required weld volume, and feeding additional filler wire will allow modifying its structure. The effectiveness of such a technological solution was evaluated by comparison with the structure produced by the traditional method. The influence of several variants of batch-produced filler materials was studied to determine the components of rational modification of the weld structure and to produce the necessary ratio of alloying elements, and the most effective, substantiated by the investigation methodology, parameters of strength and ductility of the welded joints were selected, which ensure the welded structure reliability.

Variants of the studied materials from alloys of different alloying systems were selected, namely: batch-produced ZvAK5, AVAK12 wires of Al–Si alloying system, which retain silicon, as well as embedded elements from V92, V96 and 7056 alloys, which retain zinc. Availability of low-melting silicon in the additional wire composition will allow a certain increase of the nonequilibrium solidus temperature and a reduction of the range of the metal solid-liquid state. Zinc presence will promote an increase in the level of weld strength in the joints.

During studies the following technological variants were used: Zv1201 + ZvAK5; Zv1201-AvAK12; Zv1201 + V92; Zv1201 + V96; Zv1201-7056. The results were compared with joints produced using one batch-produced alloy of Al–Cu alloying system of Zv1201 grade. Proceeding from analysis of the features of the structure and mechanical properties of specimens cut out in different regions of welds, it is intended to determine an optimal combination of the compositions of filler wires, used for welding. Their application will allow producing permanent joints of D16 alloy in keeping with the requirements and structure purpose.

In order to implement the process, the technological equipment for simultaneous mechanical feeding of two wires into a common pool and the conditions of wire feed synchronization were improved, and the modes of the process of joining D16 alloy were retrofitted. Analysis of chemical composition of the wires and embedded elements was conducted by the spectral method, using Sprectrovak-1000 equipment of Baird Company (Table 2).

Before welding the blanks were treated by 10 % NaOH solution and clarified in 13 % HNO_3 solution. Blanks were welded by a consumable electrode in the horizontal position, using studied consumables. The wires were fed into the pool in keeping with the standard requirements, i.e. directly from the face surface.

To diversify the technology variants, embedded elements of 2×2×2.5 mm size were used, which were placed in the lower section of the butt, as zinc-containing wires do not exist. V92, V96 and 7056 alloys with different zinc content were selected. Chemical elements (zinc, magnesium, copper, manganese, zir-

Table 1. Chemical composition (wt.%) and mechanical properties of 6 mm D16 alloy

Mg	Cu	Mn	Si	Fe	Zn	*E*, GPa	σ_t	$\sigma_{0.2}$	$\sigma_{0,01}$	δ_5, %
							MPa			
1.4–1.7	4.0–4.5	0.34–0.53	0.16–0.19	0.21–0.22	0.07–0.11	67–71	217–221	106–115	79–89	16–18

Table 2. Chemical composition of studied filler materials, wt.%

Filler material grade	Si	Fe	Cu	Mn	Mg	Zr	Ti	Zn
Zv1201(Al–Cu)	0.16	0.14	3.8	0.42	0.7	0.08	0.02–0.1	–
ZvAK5 (Al–Cu)	0.70	0.15	3.8	0.42	0.63	0.08	0.15	–
ZvAK12 (Al–Cu)	1.8	0.23	3.0	0.37	0.60	0.07	0.15	–
Embedded element from V92 alloy (Al–Cu–Mg)	0.17	0.35	2.80	0.31	1.0	–	0.01	0.50
V96 (Al–Zn–Cu–Mg)	0.15	0.14	2.90	0.32	1.0	–	0.04	2.6
7056 (Al–Zn–Cu–Mg)	0.13	0.10	2.80	0.31	0.76	–	0.06	2.4

conium) present in these alloys, ensure the physicochemical conditions for formation of fine-grained structure of weld metal in welding, and a significant effect of their hardening under the conditions of their further heat treatment [4–9].

The welding heat input was selected from the condition of minimal value of electric current, required for complete penetration of the alloy. That is why, this process was performed in the following mode: I_w = = 240–250 A, U_a = 20–21 V; v_w = 31–33 m/h. The weld width from the face and penetration side was almost the same, being in the range of 9–11 mm. The process was conducted with application of the forming backing, as it is known that in case of its presence the process of crystallization and growth of columnar crystallites is two-dimensional, influencing the weld quality. Modulation of the main mode parameters with cycle time of 2.2 ± 0.2 s created certain thermophysical conditions for improved control of the process of drop transfer from the main wire, producing the appropriate shape of the weld pool and weld structure formation. All together, it ensured a greater amount of oversaturated solid solution, higher density of precipitation of the dispersed hardening phase particles during the next stage (solid solution decomposition), and improvement of the joint mechanical properties [5–7].

The quality of weld formation in butt joints of D16 alloy was assessed visually and by X-ray technique (GOST 7512 [13]) in RAP-150/300 X-ray unit. Weld metal density was controlled in Densitometer DP-30 instrument.

Specimens for mechanical tests were cut out of the welded butt joints in keeping with the normative documents. Mechanical tests were conducted to GOST 1497 [14] and GOST 6996–66 [15] in Instron-1126 machine with 6 mm/min traverse travel speed. During testing, a personal computer was used for continuous recording of the loading and deformation values. These results were used for calculation of the respective parameters of ultimate rupture strength (ultimate strength of welded joints ($\sigma_t^{w.j}$) and weld metal ($\sigma_t^{w.m}$).

Metallogrpahic analysis of base metal and welded joints was performed in MMT-1600V microscope. Investigations were conducted on microsections cut out across the sheet rolling direction. The microstructure was revealed by electrolytic polishing in a solution of the following composition: chloric acid — 1000 cm^3 + ice acetic acid — 75 cm^3.

RESULTS AND THEIR DISCUSSION

Analysis of the obtained results was the base to determine the effectiveness of the studied filler wires for welding D16 alloy, their influence on weld formation mechanism, weld form factor, level of mechanical properties and features of welded joint structure, depending on chemical composition.

Metallographic studies of welded joint microstructure revealed the presence of a considerable amount of precipitates of oversaturated phases, retaining copper. Their decomposition occurs under the impact of the thermal cycle, which is accompanied by formation and coagulation of hardening phases, as well as their dissolution in aluminium solid solution.

Welds are tight, no coarse porosity is observed in the weld metal or fusion zone (Figures 2–4), but presence of low-melting eutectics in the intergranular or intercrystalline space is reported, which may be indicative of the heterogeneity of iron, copper and silicon distribution in the structure. Eutectic formation temperature, their composition and amount are the decisive factors at selection of the heating temperature for hardening and hot deformation [1–4]. They are also the main factors, which determine the behaviour of these alloys in fusion welding [1, 3, 11, 12]. According to the data of microstructural analysis, the eutectic phase precipitates are recorded predominantly on the intercrystalline boundary. As the solidification rate changes in wide ranges relative to weld width at the specified welding mode, a significant change of the nature of phase precipitates with crystallite growth is observed. Eutectic precipitates in the weld center, where the solidification rate is higher, have thinner walls of intercrystalline layers, and the cell width is smaller than near the fusion boundary. Partial melting is observed near the zone of fusion with the base metal, increase of the amount of low-melting eutectics is reported, which is a feature of duralumin class.

Comparative analysis of the structure of D16 alloy welds produced by both the technology variants, shows that a change of liquid eutectic phase distribu-

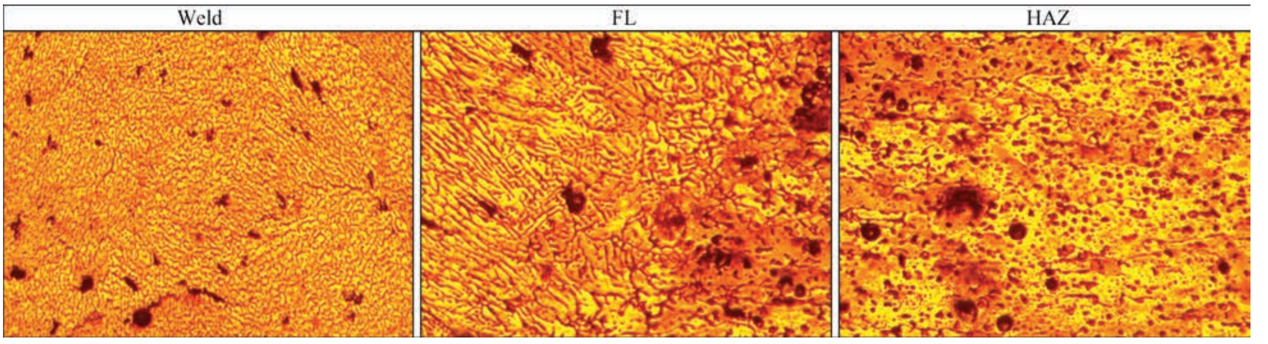

Figure 2. Microstructure of D16 alloy welded joints made with batch-produced Zv1201 wire in consumable electrode welding (×320)

tion takes place in the studied welds (Figures 2–4). It may be due to a change in the temperature intervals of their solidification due to additional modifying of weld structure. The length of solidification cracks and number of pores in welded joints decreases. Silicon addition in the amount of 5 % enabled avoiding cracking both in welds and along the fusion line, due to a balanced amount of low-melting eutectic (Figure 3). This is, probably, due to silicon promoting a higher mobility of the liquid eutectic and lowering of the temperature of primary dendrite formation in the welds [4–9, 12]. Application of ZvAK12 wire with a greater amount of silicon (12 %) does not provide the appropriate conditions for producing a permanent joint that may be due to an intensive enrichment of liquid intergranular interlayers in silicon during welding of the alloy. It results in widening of eutectic interlayers in this weld region.

Analysis of the features of welded joint structure showed that zinc addition into the weld metal, having the melting temperature of 419 °C, also influenced the ability to form a sound joint. Such chemical elements as zinc, magnesium, copper, manganese, zirconium, present in the composition of embedded elements, have different effect on the structure (Figure 4). The eutectic phase volume is also increased, limiting D16 alloy susceptibility to solidification cracking both in the weld, and in the fusion zone. Owing to an increase of the amount of low-melting eutectic and its balanced composition, conditions are provided for healing the solidification cracks and pores (Table 3). When V92 and V96 alloys are used, which have 0.50 and 2.4 % zinc, respectively, increase of its amount in the fusion zone leads to enrichment of the eutectic in the HAZ subzone where partial melting occurs during welding. It widens the eutectic interlayer between the grains. A similar effect is also observed at 2.6 % zinc (in technology variant of Zv1201 + 7056). A fine-grained structure forms in all the welds (Figure 4). Although the quantity of copper varies in the range from 4.8 to

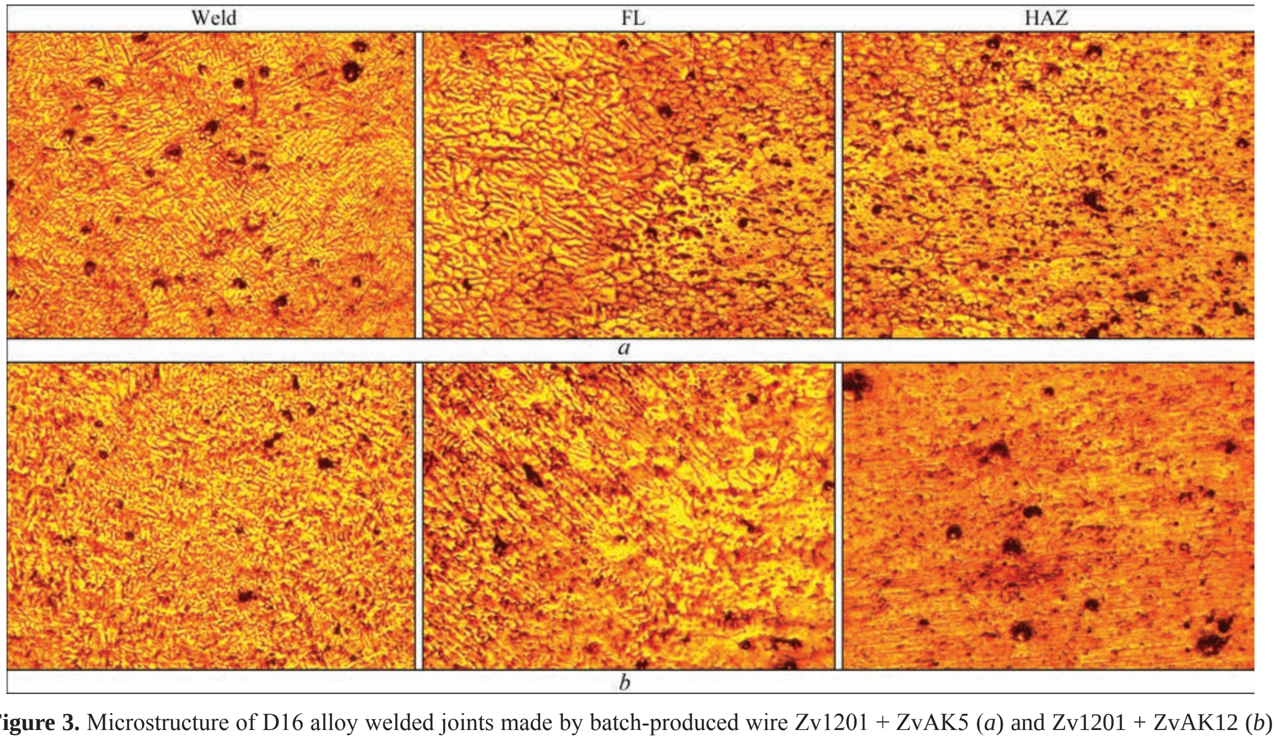

Figure 3. Microstructure of D16 alloy welded joints made by batch-produced wire Zv1201 + ZvAK5 (*a*) and Zv1201 + ZvAK12 (*b*) in consumable electrode welding (×320)

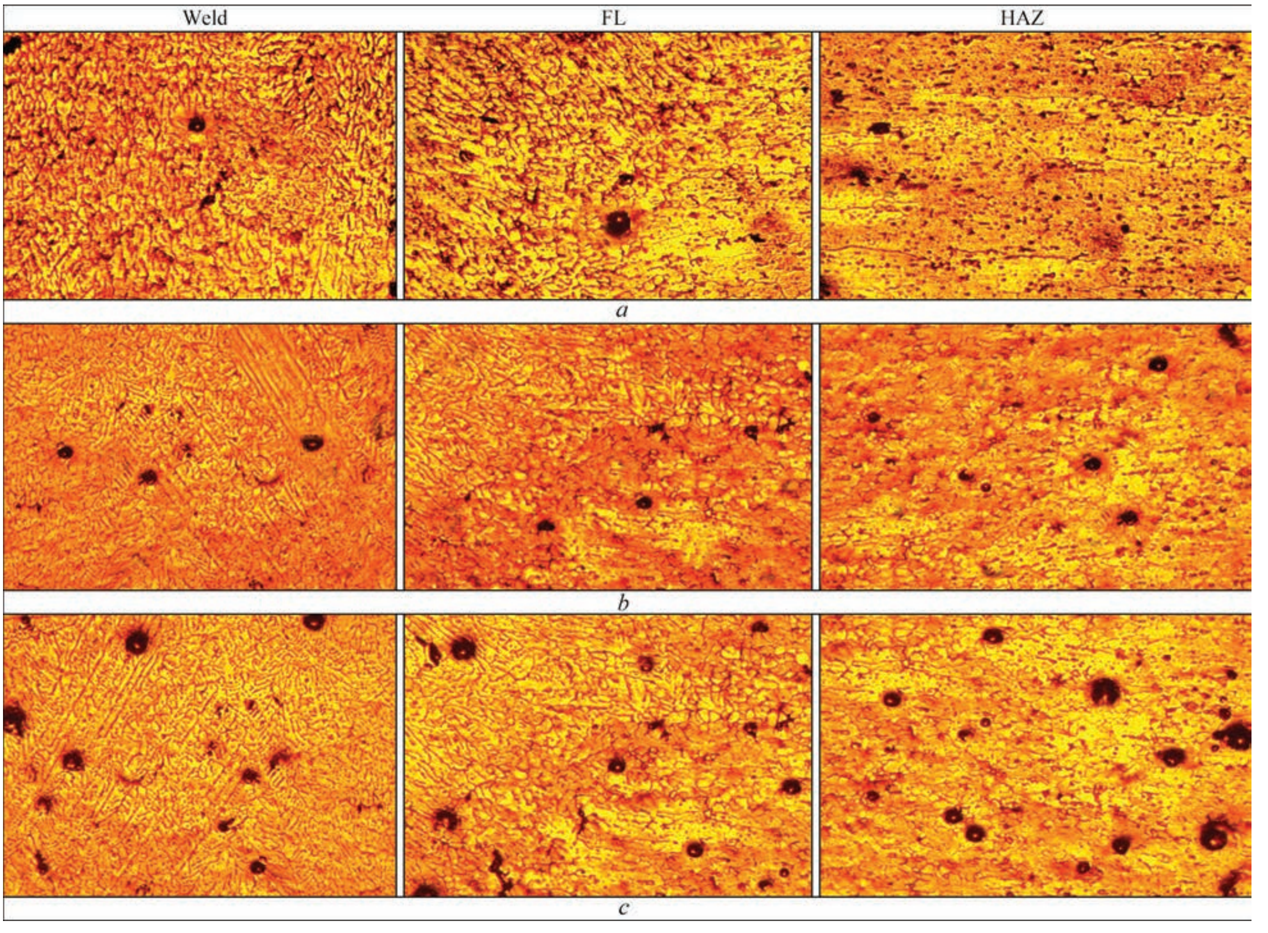

Figure 4. Microstructure of D16 alloy welded joints made with batch-produced Zv1201 wire and embedded element from B92 (*a*), B96 (*b*) and 7056 (*c*) alloys in consumable electrode welding (×320)

6.2 %, that of silicon from 0.27 to 2.2 %, and that of zinc from 0.99 to 3.2 %, their combination ensures a significant effect of weld structure hardening under the condition of further heat treatment of welded joints (Table 4) that coincides with the results obtained in works [7 – 10]. Comparative evaluation showed that the welded joint strength is equal to 186–188 MPa at application of batch-produced ZvAK5 and ZvAK12 wires with silicon. Weld metal strength here varies in the range of 180–187 MPa (Table 4). Note that Table 4 gives the average values of welded joint strength and ductility after mechanical tests of three specimens. Ductility value (bend angle) is equal to 44° for specimens made by the technological scheme of Zv1201 + SvAK5, and 27° with Zv1201 + ZvAK12 that may be due to formation of wider eutectic interlayers with low cohesion strength between the weld crystallites.

An essential increase of welded joint strength is observed, when embedded elements from V92, V96 and 7056 alloys, which retain zinc, are used as additional materials. The greatest increase of strength (up to 200.0 MPa) of both D16 alloy welded joints and weld metal (up to 194.0 MPa) is in place at application of V96 alloy, provided the ductility characteristic (bend angle) remains on the level of 23°. This is promoted by presence of zinc, which forms such complex intermetallic phase compounds as $Mg(Zn_2AlCu)$ ad $Mg_3Al_2Zn_3$ during weld metal solidification. The strength value limit depends on chemical composition of embedded element material.

Table 3. Content of the main chemical elements in the weld metal in D16 alloy consumable electrode welding with two isolated filler materials into a common pool, wt.%

Technology variants	Fe	Zn	Mn	Si	Mg	Cu	Zr
Zv1201	0.31	–	0.48	0.27	0.93	6.01	0.08
ZvAK5	0.26	–	0.34	1.02	0.73	4.95	0.08
ZvAK12	0.32	–	0.37	2.2	0.79	5.29	0.07
Embedded element from V92 alloy	0.65	0.99	0.51	0.21	1.12	5.18	–
V96	0.2	2.25	0.36	0.21	1.16	4.9	–
7056	0.27	3.2	0.3	0.46	1.51	4.81	–

Table 4. Influence of technology variants on mechanical properties of D16 alloy welded joints, depending on chemical composition of embedded elements* and filler wires**

Technology variants	$\sigma_t^{w.j}$, MPa	$\sigma_t^{w.m}$, MPa	α, deg
Zv1201 (Al–6.3 % Cu–0.3 % Mn) – base	193.0	186.0	40
Zv1201 + ZvAK5 (Al–5.5 % Si)	188.0	187.0	44
Zv1201 + ZvAK12 (Al–12 % Si)	186.0	180.0	27
Zv1201 + B92 alloy (Al–0.5 % Cu–4.2 % Mg–3.5 % Zn)	190.0	191.0	27
Zv1201 + B96 alloy (Al–2.3 % Cu–2.6 % Mg–8.5 % Zn)	200.0	194.0	36
Zv1201 + 7056 alloy (Al–1.65 % Cu–1.8 % Mg–9.5 % Zn)	190.0	194.0	31

*Fracture occurs through base metal in the HAZ.
**Fracture occurs along weld axis and fusion boundary of D16 alloy.

The nature of strength change in different regions of welded joints was studied by measuring the hardness value in these zones, namely: in the weld, fusion zone and HAZ (Table 5). This is due to the known correlation of metal strength and hardness in welding aluminium alloys [2–4, 9]. As shown by their analysis in as-welded butt joints, i.e. without heat treatment, use of batch-produced wires ZvAK5 and ZvAK12 containing 5 and 12 % silicon, respectively, has almost no influence on hardness level in different zones of the joints.

When welding with application of embedded elements from V92, V96 and 7056 alloys as additional materials, metal hardness in different zones of the joint rises by 2–5 units, compared to joints made with batch-produced ZvAK5 and ZvAK12 wires, containing silicon. The greatest difference is found in the weld metal. Hardness value is determined by the amount of zinc in the respective additional materials.

In the fusion zone the difference in the hardness values is equal to 1–2 units, and in the HAZ these values are almost the same (Table 5). Similar to the previous case, a 3–5 % increase in the hardness level is observed after artificial aging, in keeping with the amount of zinc in the additional material. Hardness increases even more after performance of the operations of full heat treatment of welded joints. Analysis of hardness measurement results shows that such a treatment mode is the most suitable for producing high values of mechanical properties, namely appropriate level of strength alongside sufficient ductility, which will ensure the welded structure performance. This is also indicated by the microstructure of specimens of welded joints made with two batch-produced silicon-containing wires and embedded elements from metals alloyed by zinc (Figures 2–4).

Table 5. Influence of chemical composition of silicon-containing filler wires and embedded elements from zinc-containing alloys on hardness of D16 alloy welded joints (65–67 *HB*) made by consumable electrode, MPa

Technology variants	Weld	FZ	HAZ
Zv1201	88–89	60–89	59–65
Zv1201 + ZvAK5	89–90	62–87	60–65
Zv1201 + ZvAK12	88–90	62–87	59–65
Zv1201 + (7056)	90–91	61–87	59–65
Zv1201 + (V96)	89–90	61–85	59–65
Zv1201 + (V2)	89–90	62–88	60–65

Notes. 1. Brinell hardness *HB* of welded joints was measured in Rockwell instrument at load $P = 600$ N by 1/16″ sphere. 2. The grade of the alloy used as embedded element is shown in brackets.

Relief of welded joint fracture surface after mechanical tests can be conditionally divided into characteristic structural zones: initial, where the microcrack initiates, region of its stable growth and region of its accelerated growth up to the main crack formation, the appearance of which leads to complete destruction of the specimens. Microrelief of each of the mentioned regions changed under the influence of the above technology factors. Realisation of this process is due to a considerable intensity of metal plastic deformation, when the stress level exceeds the value of the forces of cohesion of the matrix and the inclusion in the direction, normal to their boundary [9, 12]. Microcracks initiate on coarse phase particles and intermetallics located along the crystallite boundaries. The crack length is determined by its volume fraction in the base metal. Partially-melted grains of the base metal located near the zone of its fusion with the weld, point to a slight overheating of the metal in welding. Here, development of heterogeneity as to the dimensions of excess phases and clusters of intermetallic compounds is noted. The above-said is due to the respective amount of alloying elements and admixtures as a result of their segregation along the weld crystallite boundaries and base metal grains, as well as formation of individual regions of intergranular interlayers from oversaturated phases.

Weakly-developed deformation bands are visible on the fracture of a flat-ridge region. Cells of predominantly medium size (6–8 μm) are limited by tear ridges and retain broken inclusions of intermetallic phases on their bottom. Formation of such local centers of destruction in the form of cells can be associated with relaxation of compact high-density dislocation clusters and microvoid formation during plastic deformation. Fracture surface relief near the main crack mouth

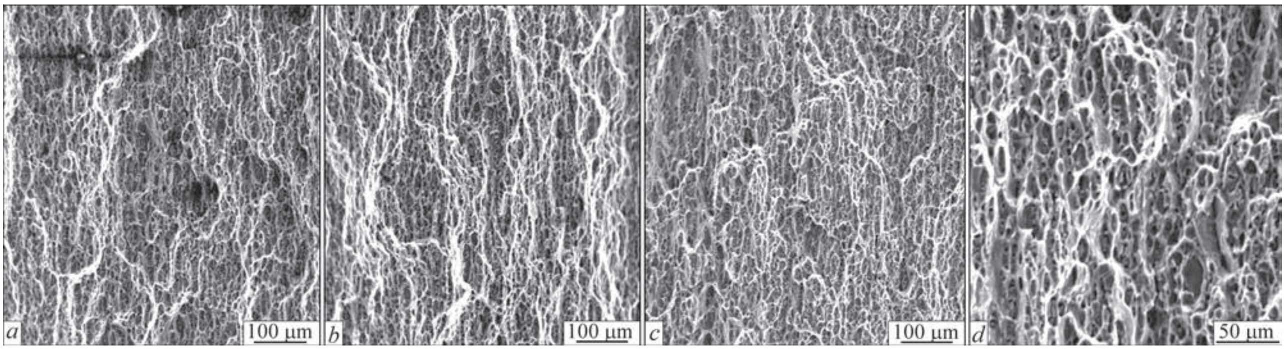

Figure 5. Panorama of fracture surface along the weld axis from technological convexity (*a*), medium regions (*b*, *c*) to the root (*d*) of a D16 alloy joint produced by consumable electrode welding, after mechanical testing (×500)

also contains microtears, arising along the crystallite boundaries during deceleration of crack propagation (see Figure 5). Centers of crack initiation are inclusions which do not dissolve at heating in welding and form intermetallic conglomerates. Considerable localization of stresses, particularly in the grain joining areas, leads to their destruction. Tough cells on the relief retain quasicleavage elements that may be indicative of ductile shear concentration in individual most stressed regions of D16 alloy structure. The size of facets on the fracture surface varies from 2 to 5 μm. Their small dimensions are determined by the rate of solid solution decomposition under the welding conditions, when phase transformations do not have enough time to develop.

CONCLUSIONS

1. Preliminary studies of consumable electrode welding of 6 mm D16 aluminium alloy were performed using two 1.6 mm filler wires of Zv1201, ZvAK5, ZvAK12 grade, as well as embedded elements from V92, V96 and 7056 alloys,. Wires were fed into the weld pool directly from its face surface. Optimal parameters of welding mode were determined as follows: I_w = 240–250 A; U_a = 20–21 V; v_w = 31–33 m/h. Weld width from the welding face and penetration side was almost the same in all the welds. Presence of silicon and zinc in the fillers promotes formation of a considerable amount of low-melting component in the structure that lowers the risks of appearance of solidification cracks and pores in the welds.

2. Structural analysis of D16 alloy welds produced by different fillers showed that a sufficient amount of the low-melting component forms at application of ZvAK5 wire (5 % Si) and it allows avoiding defects in welds. In case of application of ZvAK12 wire (12 % Si) no sound formation of the weld is observed that is due to greater width of intergranular eutectic interlayers due to enrichment in silicon. A similar phenomenon also takes place at application of embedded elements from V92, V96 alloys (0.50 and 2.4 %, respectively) and 7056 (Zn = 2.6 %). The amount of zinc influences the interlayer width.

3. A dependence of mechanical properties of D16 alloy joints on chemical composition of the wires and embedded elements was established. At application of ZvAK5 and ZvAK12 wires the joint strength is equal to 186 to 188 MPa, and that of weld metal — 180–187 MPa. Ductility value (bend angle) is equal to 44 and 27°, respectively, which may be associated with low cohesion strength of the eutectic interlayers. The joint fails in the HAZ, near the weld, where a brittle intermetallic network is observed along the grain boundaries, because of coagulation of the strengthening phases. More over, metal overheating takes place with partial melting of the individual components, as well as a series of structural transformations, namely low-temperature recovery, annealing, recrystallization, partial hardening. Zinc presence in the embedded elements increases the joint strength level to 190–200 MPa and of weld metal in the range of 191–194 MPa, compared to silicon-retaining wires.

4. Joints fail through coarse phase particles and intermetallics located along the boundaries of weld crystallites in the zone of fusion with the base metal. The above phenomenon is determined by volume fraction in the base metal and the effect of modifying by fillers, which is due to the presence of the respective amount of alloying elements and admixtures, their segregation, formation of individual regions of intergranular interlayers from oversaturated phases in the structure and inhomogeneity of excess phases and intermetallic clusters. Partially-melted base metal grains, located near the zone of D16 alloy fusion with the weld, point to a slight metal overheating in consumable electrode welding.

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ORCID

T.M. Labur: 0000-0002-4064-2644,
V.A. Koval: 0000-0001-5154-1446,
M.R. Yavorska: 0000-0003-2016-6289

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

T.M. Labur
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: tanyalabur@gmail.com

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