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Structure and Mechanical Properties of Heat-Treated D16 Aluminium-Alloy Welded Joints Made with a Consumable Electrode after Heat Treatment

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The extent of the influence of heat treatment on structural features and mechanical properties of 6-mm D16 alloy and its welded joints made by a consumable electrode with application of two isolated filler wires or embedded elements of different chemical composition is established. Wires of Zv1201, ZvAK5, ZvAK12 grades of 1.6-mm diameter and embedded elements cut out of V92, V96 and 7056 alloys are used for welding.

Key words: aluminium alloy, consumable-electrode welding, joining, heat treatment, microstructure, mechanical properties.

Встановлено ступінь впливу термічного оброблення на структурні особливості та механічні властивості стопу Д16 товщиною у 6 мм та його зварних з’єднань, виконаних топкою електродою із застосуванням двох ізольованих присадних дротів або втілених елементів різного хемічного складу. Для зварювання використано дріт марок Зв1201, ЗвАК5, ЗвАК12 діяметром у 1,6 мм і втілені елементи, яких було вирізано зі стопів В92, В96 і 7056.

Ключові слова: алюмінійовий стоп, зварювання топкою електродою, з’єднання, термооброблення, мікроструктура, механічні властивості.

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1. INTRODUCTION

Heat-hardenable D16 aluminium alloy (Al–Cu–Mg) is used with success in different mechanical engineering sectors, as it is characterized by a unique combination of mechanical properties, due to chemical composition of chemical elements (Table 1). The range of its semi-finished products is rather wide [1–5]. The main precipitation phases are $CuAl_2(\theta)$ and $Al_2CuMg(S)$. At the ratio of Cu/Mg ≤ 2.6, the structure contains S-phase, which is the main phase in D16 alloy strengthening. At the ratio of Mg/Si = 1.73, Mg_2Si phase forms in addition to it.

In the cast state, the alloy structure is non-equilibrium. It consists of the solid solution and precipitates of intermetallic phases, located along the grain boundaries and between the dendrite axes in the form of pseudoeutectic. This one results in a low strength level (185–200 MPa) of the alloy, as well as low ductility, compared to other structural aluminium alloys (Table 2). At process heating, the alloy demonstrates a high capability of structural equilibrium due to the influence of the mechanism of all the alloying element transition from the equilibrium state into the solid solution [1, 4, 6, 7]. Therefore, the alloy chemical composition was selected taking this physical phenomenon into account. In the wrought state, this effect develops faster than in the cast one. During decomposition of oversaturated solid solution, the strength is increased, but the ductility values are decreased. In the thermally strengthened condition, the alloy is characterized by somewhat higher strength (210–230 MPa), depending on temperature–time heat treatment modes. In the annealed state, the value of D16 alloy ductility is satisfactory—3–6%.

To prevent cracking in the metal and lower the degree of its buckling, the alloy is quenched from the temperature of 500 ± 5°C in cold water of 20–40°C. In the case, when the alloy stays at room temperature for 90–100 h, it demonstrates the capability for natural (zonal) ageing [6]. Ultimate tensile strength of the alloy after quenching is increased by 110 MPa, compared to the annealed state. An increase in ultimate tensile strength by 100 MPa is observed in this case. The level

TABLE 1. Chemical composition 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	6–18

TABLE 2. Effect of heat-treatment on hardness of D16 alloy welded joints, made by consumable electrode with batch-produced Zv1201 filler wire and Si-containing wire.

State of base metal and welded joint	Hardness, *HRB*									
	BM	Zv1201			Zv1201 + ZvAK5			Zv1201 + ZvAK12		
		Weld	WJ	HAZ	Weld	WJ	HAZ	Weld	WJ	HAZ
After welding and natural ageing	65–67	88–89	60–89	59–65	89–90	62–87	60–65	89–90	62–87	59–65
Welding + artificial ageing		88–88	79–87	63–66	95–96	74–90	60–65	96–98	78–94	61–66
Welding + quenching + artificial ageing	100–102	94–95	97–98	96–99	94–95	97–98	99–101	93–95	95–98	99–101

of mechanical properties of the alloy after quenching and natural ageing reaches $\sigma_t = 470$ MPa, $\sigma_{0.2} = 300$ MPa, $\delta = 19\%$. Wrought sheets are often subjected to artificial (phase) ageing at temperature conditions of 190 ± 5°C for 12–13 h [4–6].

At the same time, the main disadvantage of the alloy remains to be its sensitivity to process heating. It is exactly what provokes initiation of ‘hot cracks’, as a result of a non-uniform distribution of alloying elements in the alloy structure, as well as formation of complex phase compounds, *etc.*, the appearance of which lowers the mechanical properties of base metal and its welded joints. That is why, technologies aimed at cracking prevention and raising the level of its respective characteristics are applied in fabrication of critical structures from this alloy. Different technological approaches are used for this purpose: from application of advanced solid-phase welding technologies to manufacture of integral welded structures [5].

Note that the technological advance in welded structure fabrication is directly associated with solving a number of complex, but interrelated science and technology problems. Development of new more functional structural materials, as well as improvement of the chemical composition and properties of the traditional alloys result in the demand and need for a thorough study of their joining processes. At the same time, arc-welding technologies remain the most common methods of joining parts and components in structure fabrication [4]. This is promoted by flexibility of processes realization, their cost, as well as the availability and degree of acceptance by industry of the normative documents, required for reproduction of the respective welding modes under the shop conditions. The main requirements here are stability of the weld structure quality and higher efficiency of production lines for welded structure fabrication.

Considering the technological advantages of arc technologies, it should be noted that the low speeds of tungsten electrode welding of aluminium alloys from the viewpoint of industrial requirements, restrain production of sound welds. Plasma-arc welding is too expensive now, and it does not ensure the appropriate production flexibility of the process under the conditions of its plant realization, unlike the consumable electrode joining technology [7]. This is due to a relatively low value of heat input into the process proper that allows it to be automated and integrated into the production line. However, there remain the consequences of the impact of physical conditions of liquid metal solidification in the weld pool, during which such undesirable phenomena as segregation and formation of various technological defects may arise, lowering the joint properties.

Chemical composition of filler wires is one of the main tools for weld structure improvement and producing the required mechanical and service characteristics of the joints in welded structures. Note that the effectiveness of their influence on the mechanical properties is diverse, as it depends on the alloying degree of the wires proper [1–4]. Two or three filler wires (electrodes) are sometimes used for improvement of the production process of structure welding. It allows modifying the weld structure, and, this way, eliminating the causes for defect formation in the deposited metal. A similar effect was also obtained in multipass welding with rotation. In this case, the change of deformation and stress concentration along the weld axis allowed increasing the joint strength level by 10% and the relative elongation level by 4% [7, 8].

Recovery of the properties of heat-hardenable aluminium alloys and their joints is often observed, when various heat treatment modes are used [9–11]. It is achieved due to realization of two mechanisms of aluminium-alloy strength improvement: formation of precipitate dispersion or solid solution strengthening and alloy quenching; alloying element dissolution in the solid solution and their further precipitation in the form of submicroscopic coherent particles [1, 2]. The operation of artificial ageing, denoted as T81, is the most common in production, as it increases the strength level. Such an increase in strength is also observed at its combination with subsequent deformation of metal up to 8% (T37 condition), which is performed at 163°C for 24 (36) h. However, the ductility values decrease almost two times with both the technologies. A simultaneous increase of strength and ductility characteristics is reported as a result of performance of a full heat-treatment cycle (T62 condition). In this case, first, the metal is quenched in water with cooling from the temperature of 500 ± 5°C, and then, the operation of artificial (phase) ageing is performed for 12 h at the temperature of 190 ± 5°C [12, 13]. As the cooling rate during quenching determines the structure morphology and residual stress level, *i.e.*, it has an essential influence on the mechanism of formation of coarse nonequilibrium phases, it is given special attention [5]. Elimination of some phases or their additional precipitation in the structure promotes partial or complete recovery of the mechanical properties, so that, it is rational to conduct a more detailed study of the effectiveness of heat treatment modes of D16 alloy joints made by a consumable electrode with two isolated wires.

In connection with the above ideas, the objective of the study was to establish the features of microstructure formation in D16 alloy welds made by a consumable electrode with application of batch-produced filler wires or embedded elements after heat treatment by different technologies, and to compare these results with base metal properties. Batch-produced wires of Al–Si system were selected for this purpose, namely, ZvAK5 (Al–5.5% Si) and ZvAK12 (Al–12% Si) with silicon. Its presence promotes appearance of a considerable number of low-melting eutectics capable of lowering the risks of solidification crack and pore formation in welding of D16 alloy or ensuring the conditions for their healing during weld solidification. The following zinc-containing alloys were used as embedded elements: V92 (Al–0.5% Cu–4.2% Mg–3.5% Zn), V96 (Al–2.3% Cu–2.6% Mg–8.5% Zn) and 7056 (Al–1.65% Cu–1.8% Mg–9.5% Zn). Butt joints were welded by the following technology variants: Zv1201 + ZvAK5; Zv1201 + ZvAK12; Zv1201 + V92; Zv1201 + V96; Zv1201 + 7056. Research results were compared with those of the joints produced with one wire of Al–Cu system of Zv1201 grade (Al–6.3% Cu–0.3% Mn). Proceeding from analysis of the features of the structure and mechanical properties of the specimens, cut out in different sections of the welds, an optimal combination of filler wire chemical composition was determined, application of which enables producing permanent joints of D16 alloy, in keeping with the requirements to and purpose of the welded structure. The above methodology was selected in connection with the fact that phase growth occurs during liquid metal solidification and formation of weld microstructure on its boundary along the front [1]. The extent of this phenomenon is determined by temperature gradient on the interface of the solid solution and the phases, as well as the pattern of distribution of the solution, the morphology of which changes from the cellular to the dendritic one.

The operation of artificial ageing by the mode of $T = 190 \pm 5$°C for 12 h was selected to determine the range of effectiveness of the above-mentioned heat treatments, as it ensures the maximum strength level and stability of the structure in time [2–4]. Another studied technology variant was application of a full heat treatment cycle, *i.e.*, quenching of D16 alloy welded joints (welded butt joint heating up to the temperature of $T = 500 \pm 5$°C and soaking for 1 h with cooling in water and further artificial ageing by the mode of $T = 190 \pm 5$°C for 12 h). Selection of the above technological conditions of welded joint treatment was performed, taking into account the known data [1, 4, 5], which show that at D16 alloy quenching the brittle intermetallic interlayers between the grains almost completely go into the solid solution, and, thus, they can ensure a higher level of joint ductility. The driving force of this process is determined by the degree of solid solution oversaturation in the alloy, features of its structural morphology, dimensions or dispersion of phase inclusions, precipitating during heat treatment.

2. EXPERIMENTAL PROCEDURE

Before welding, D16 alloy blanks were traditionally treated in 10%-NaOH solution and clarified in 13%-HNO_3 solution. Consumable-electrode welding of the blanks was conducted in a horizontal position. For practical realization of the process, technological equipment was improved, which ensured simultaneous mechanical feeding of two insulated wires into a common pool. The wires were fed into the pool according to standard requirements, *i.e.*, directly from the face surface of the butt joints being welded. Modes of the joining process and conditions of wire feed synchronization directly during welding were also optimized.

To expand the technology variants, embedded elements of 2×2×2.5-mm size of V92, V96 and 7056 aluminium alloys with different zinc content were also used, which were located in the lower part of the butt. Zn, Mg, Cu, Mn and Zr chemical elements, which are included into the composition of these alloys, ensure physic-chemical conditions for formation of a fine-grained structure of weld metal, which promotes its strengthening under the conditions of subsequent heat treatment of welded joints [1].

The value of welding heat input was selected from the condition of a minimal value required for complete penetration of this alloy thickness, that is why the process of butt joining was conducted in the following mode: $I_w = 240–250$ A, $U_a = 20–21$ V, welding speed here was equal to 31–33 m/h. The width of butt welds was almost the same from the face and penetration side, being in the range of 9–11 mm. The process was realized with application of a forming backing, as it is known that when it is used growth of columnar crystallites in the two-dimensional direction takes place, and it influences the joint quality [4]. Modulation of the main mode parameters with cycle duration period of $2.2 + 0.2$ s created necessary thermophysical conditions, when control of the process of drop transfer from the main wire of Zv1201 grade and formation of the appropriate shape of the weld pool and weld structure are improved. It increases the amount of oversaturated solid solution and the density of precipitates of dispersed particles of the strengthening phase during solid solution decomposition.

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

The welded butt joints were used to prepare specimens for mechanical testing, in keeping with the requirements of normative document GOST 6996 [14]. Mechanical tests were conducted by a procedure, described in GOST 1497 [15]. Here, Instron-1126 machine was used, the speed of its crossbeam displacement being 6 mm/min. The load and deformation values at specimen testing were recorded by a personal computer that allowed further on calculating the values of ultimate tensile strength (ultimate strength of welded joints (σ_t^{WJ}) and weld metal (σ_t^{WM}) of welded joints). Obtained experimental results allowed establishing their sensitivity to the thermal cycle of consumable electrode welding and assessing the coefficient of welded joint strength, compared to base metal strength level ($K_W = \sigma_t^{ws}/\sigma_t^{bM}$ or $K_W = \sigma_t^{WM}/\sigma_t^{bM}$).

After welding and heat treatment by two modes, the general state of the joints and their deformability under the conditions of three-point bending with load application from the weld root side as bend angle (α) (GOST 14019-80) were studied, and the derived results were compared with base metal values. Technological reinforcement and weld root here were machined to required dimensions.

Heat treatment of the specimens before tensile testing was performed in keeping with the above technology variants: artificial ageing and full heat treatment (quenching and artificial ageing). Selection of the mode of joint heat treatment was performed, taking into account the processes of dispersed precipitation of phase particles, solid solution strengthening, brittle intermetallic dissolution that promotes higher ductility of D16 alloy [1]. Precipitation of dispersed particles of $AlCu_2$ phase was observed at artificial ageing, their presence in the metal increasing this alloy strength. The effectiveness of the above processes was determined during investigations, with recording of the structural morphology and size of phase inclusions in different zones of welded joints.

Brinell hardness *HB* was evaluated with the purpose of a better substantiation of selection and development of the respective technological measures on optimization of the modes of D16 alloy welding and heat treatment of its welded joints. The degree of strength lowering was recorded in Rockwell instrument at load $P = 600$ N, by a 1/16 inch sphere (measurement point spacing was 2 mm). All the obtained hardness values were specified by normative document GOST 9012-89 [16]. Hardness measurements were conducted on the surface of the studied welded butt joints, cut out across the welding direction. Determination of the above parameter was based on the existence of a connection between the structural state and mechanical properties [1, 2].

Metallographic examination of base metal and welded joints was performed in MMT-1600V microscope, using butt joint sections cut out across the rolling direction of the semi-finished products. Microstructural features were revealed by electrolytic polishing in a solution of the following composition: chloric acid 1000 cm^3 + ice acetic acid 75 cm^3.

3. INVESTIGATION RESULTS AND DISCUSSION

Dissolution of alloying elements in the aluminium solid solution and formation of submicron particles of the second phase take place in aluminium alloys during heat treatment, as is known from works [1, 3, 4]. That is why, in order to determine the most influential technology factor, which improves the mechanical properties of D16 alloy welded joints, heat treatment of butt joints was followed by studying their microstructural features, achieved due to two isolated wires of different chemical composition, or embedded elements, the composition of which is given above.

Metallographic Investigations. Analysis of the alloy microstructural features showed that during consumable electrode welding at the speed of 32–33 m/h, high-temperature heating of the metal and its further cooling cause formation of a heterogeneous structure in the joint zone, inherent to fusion arc welding processes. The extent of structural transformations and volumes of precipitation or dissolution of the forming phases are determined by the term of the respective metal region staying in particular temperature ranges, which are due to welding speed. The processes of diffusion of alloying elements and additives included into the composition of this alloy, filler wires and embedded elements, determine the nature of local structural features in all the zones of the welded joint (Figs. 1–5). By the data of Refs. [4–9], during welding of alloys of D16 type, up to 7 diverse phase inclusions are usually observed in its structure. Some of them belong to intermediate ones, for instance, metastable θ' phase, which later on transforms into a stable equilibrium $\theta(CuAl_2)$ phase.

Weld microstructure is determined by chemical composition of the alloy and main Zv1201 wire. Structural morphology is quite homogeneous; it consists of solid solution and fine inclusions of $CuAl_2$ phase, as well as eutectic of $(\alpha + CuAl_2)$ type, characteristic for this alloying system. Inclusions of oxide films or microcracks are not observed in the welds, but individual pores of up to 0.1 μm size are found in the sites of excess phase precipitates. Their number and arrangement depend on chemical composition of additional filler materials. Fine equiaxed crystallites are found in the weld central part, and in the periph-

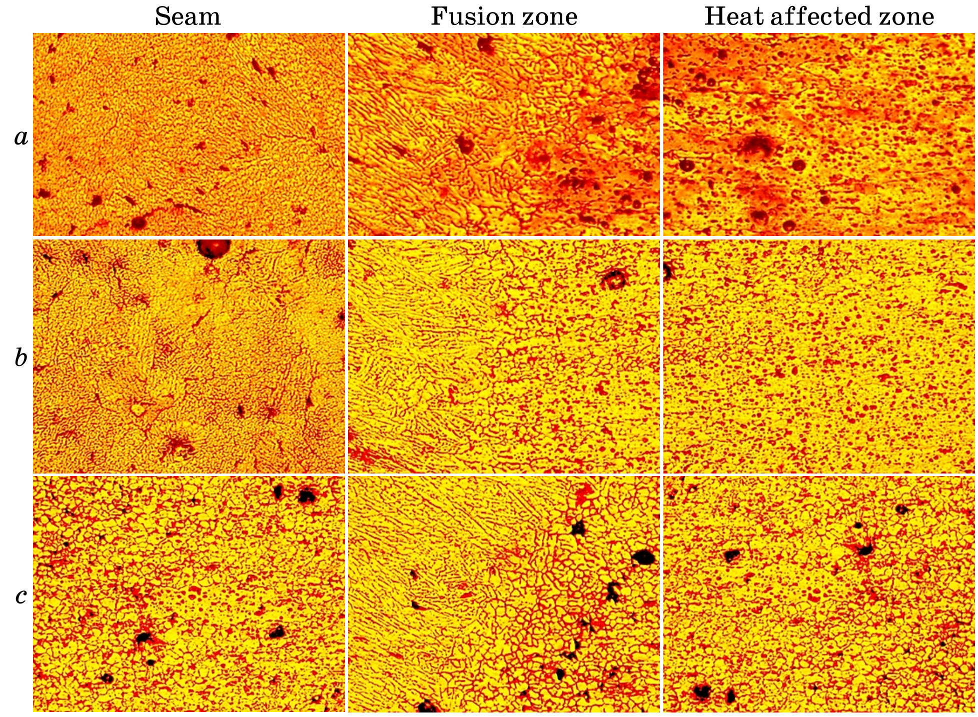

Fig. 1. Microstructure of D16 alloy welded joints made with batch-produced wire of Zv1201 grade: after welding (*a*), artificial ageing (*b*), and full heat-treatment cycle (*c*). ×320.

eral zone (line of its fusion with base metal), these are crystallites, oriented in the direction of the heat removal vector. A narrow zone of fine columnar crystallites is observed on the fusion boundary in the HAZ and eutectic interlayers are found near the intermetallic phase inclusions, which were formed at heating above the non-uniform solidus temperature [1].

Modification of the structure of welds formed as a result of feeding additional wire into the metal pool is cellular–dendritic, typical for arc welding with high density and dispersion of phase particle precipitates (Figs. 1–5).

A diverse nature of phase precipitates is observed across the entire weld thickness as the crystallites grow. This is attributable to a change of metal pool solidification rate in a wide range relative to the direction of the torch displacement at the specified welding mode. At application of ZvAK5 and ZvAK12 wires, an increase in the amount of low-melting eutectics is recorded in the structure of the weld and in the region of partial melting of the grains, predominantly on intercrystalline boundary. As at the specified welding mode, the solidification rate

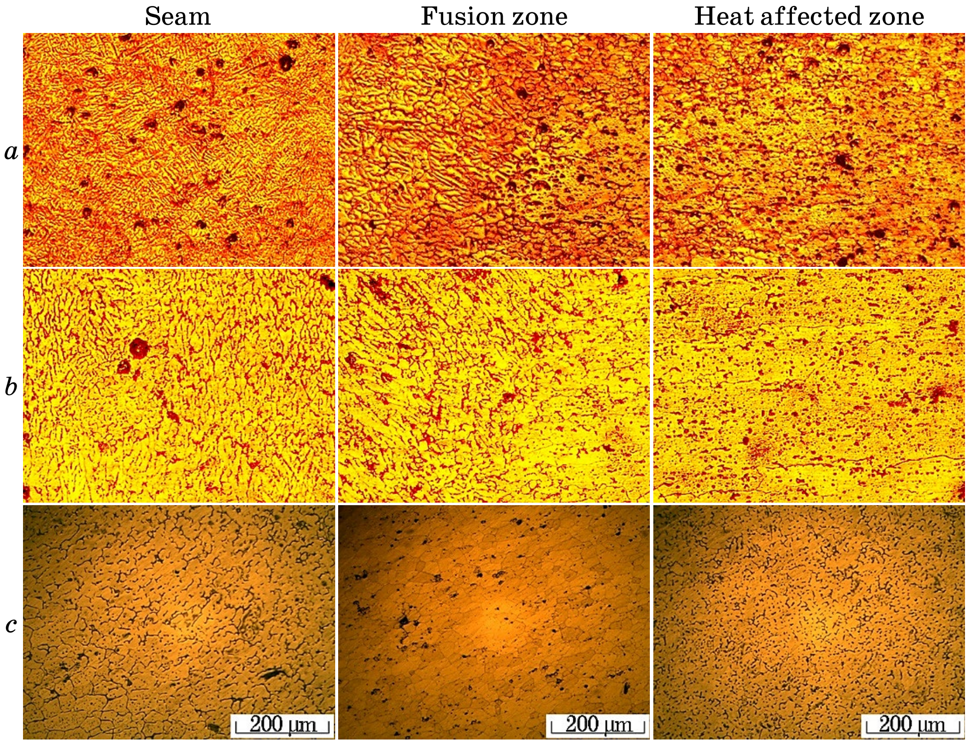

Fig. 2. Microstructure of D16 alloy joints produced with isolated Zv1201 + ZvAK5 wires into one a common pool: after consumable-electrode welding (*a*), artificial ageing (*b*), and full heat-treatment cycle (*c*). ×320.

changes in a broad range relative to weld width, a significant change in the nature of phase precipitates occurs with crystal growth. Eutectic precipitates of particles in the weld centre, where the solidification rate is higher, have thinner walls (10–15 μm) of intercrystalline layers, and the cell width is 8 μm smaller than near the fusion boundary (39–35 μm). A non-uniform degree of the change of phase-structural state of the metal leads to anisotropy of structural regions in the case of application of embedded elements in welding, Mg (Zn_2AlCu) and $Mg_3Al_2Zn_3$ intermetallic phase compounds are found in the structure. Zinc content in the applied elements determines them in the weld volume. Eutectic phase precipitation is observed predominantly on the intercrystalline boundary.

Performance of artificial ageing does not change the overall structure pattern, but it promotes increase of the number of strengthening phase precipitates in the intercrystalline gap (Fig. 2). Their number depends on their presence in the alloy or filler materials. It allows obtaining an oversaturated solid solution, which provides the respective

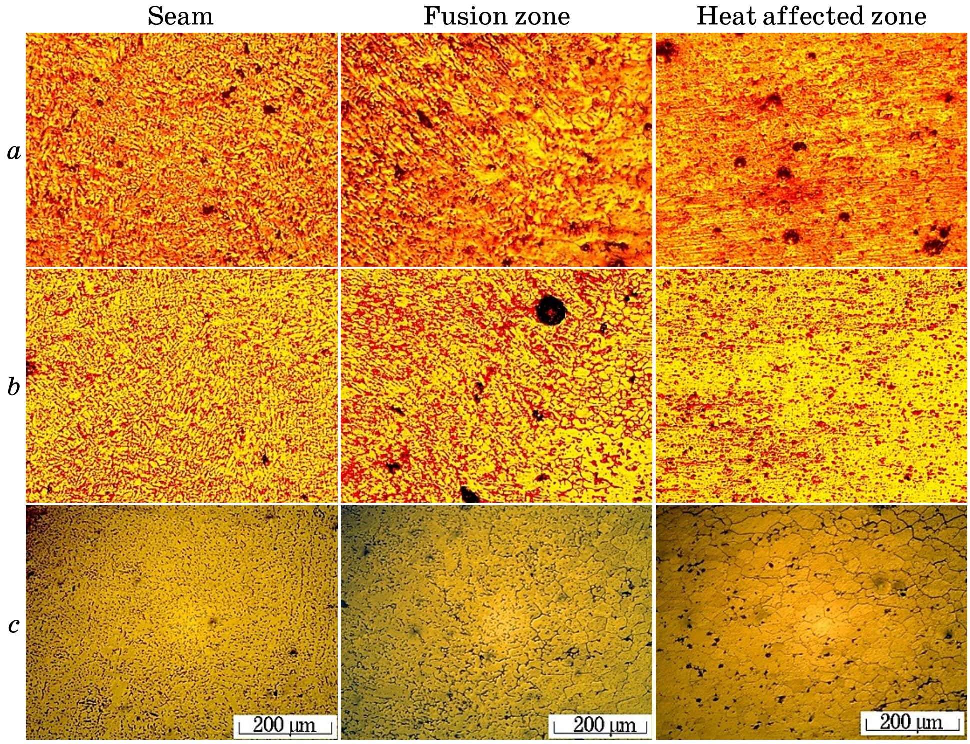

Fig. 3. Microstructure of D16 alloy welded joints produced with isolated Zv1201 + ZvAK12 wires into a common pool: after consumable-electrode welding (*a*), artificial ageing (*b*), and full heat-treatment cycle (*c*). ×320.

set of properties of welded joint specimens. Conducting full heat treatment, *i.e.*, quenching and artificial ageing of the studied welded joints of D16 alloy, significantly changes the location morphology of the phases, strengthening the metal. Their dispersion and number increase in all the zones (Fig. 3). This is due to the rate of decomposition of oversaturated solid solution during metal cooling in water at quenching. The shape and pattern of distribution of phase precipitates are related to chemical composition of the used materials. In the case of application of both ZvAK5 or AzAK12 wires and embedded elements from V92, V96 and 7056 alloys in welding, the number of phase inclusions in the crystalline structure volume is directly proportional to silicon presence in the composition of the wire and of zinc in the embedded elements.

Evaluation of Hardness Value. Measurement of the mentioned metal characteristic in different joint zones, namely, in the weld, on the fusion boundary and in the HAZ confirmed the above-given regularities of irreversible structural–phase transformations, taking place at high

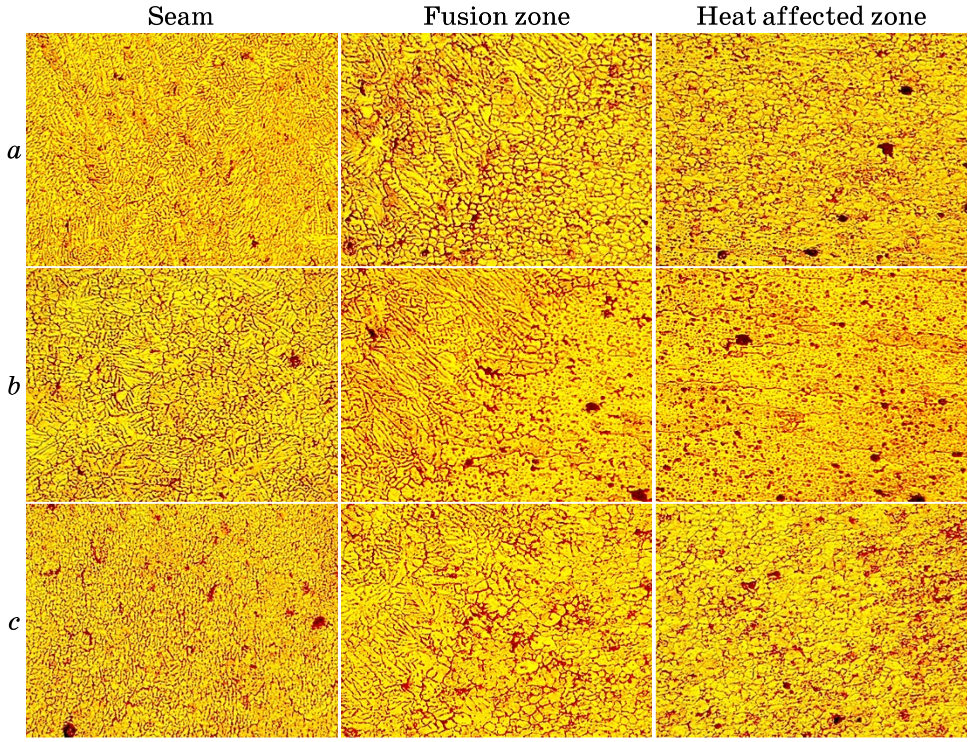

Fig. 4. Microstructure of welded joints of alloy D16 after welding with a fusible electrode and artificial ageing: ZSv1201 + 7056 (Zn = 9.5%) (*a*), Zv1201 + B96 (Zn = 8.5%) (*b*), Zv1201 + B92 (Zn = 3.5%) (*c*). ×320.

temperatures in welding D16 alloy. Modification of the structure of welds formed as a result of feeding additional wire into the metal pool is cellular-dendritic, typical for arc welding with high density and dispersion of phase particle precipitates (Figs. 1–5).

A diverse nature of phase precipitates is observed across the entire weld thickness as the crystallites grow. This is attributable to a change of metal pool solidification rate in a wide range relative to the direction of the torch displacement at the specified welding mode. At application of ZvAK5 and ZvAK12 wires, an increase in the amount of low-melting eutectics is recorded in the structure of the weld and in the region of partial melting of the grains, predominantly on intercrystalline boundary. As at the specified welding mode, the solidification rate changes in a broad range relative to weld width, a significant change in the nature of phase precipitates occurs with crystal growth. Eutectic precipitates of particles in the weld centre, where the solidification rate is higher, have thinner walls (10–15 μm) of intercrystalline layers, and the cell width is 8 μm smaller than near the fusion boundary

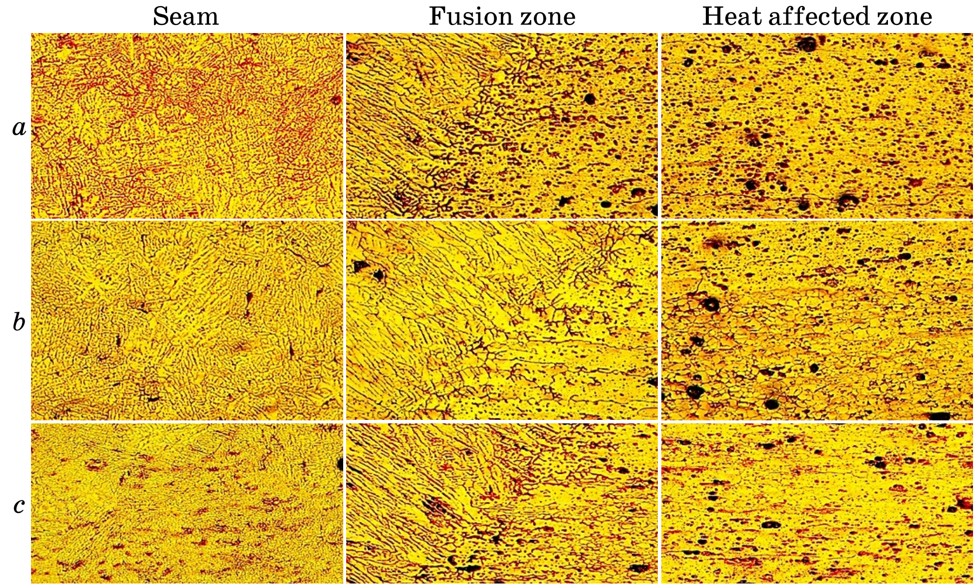

Fig. 5. Microstructure of welded joints of alloy D16 after welding with a fusible electrode and a full cycle of heat treatment: Zv1201 + 7056 (Zn = 9.5%) (*a*), Zv1201 + B96 (Zn = 8.5%) (*b*), Zv1201 + B92 (Zn = 3.5%) (*c*). ×320.

(39–35 μm). A non-uniform degree of the change of phase–structural state of the metal leads to anisotropy of structural regions in the HAZ. In the case of application of embedded elements in welding, Mg (Zn_2AlCu) and $Mg_3Al_2Zn_3$ intermetallic phase compounds are found in the structure. Zinc content in the applied elements determines them in the weld volume. Eutectic phase precipitation is observed predominantly on the intercrystalline boundary.

Distribution of hardness values practically reflects the kinetics of solid solution decomposition process and distribution pattern of decomposition products in the matrix during welding and heat treatment. Their dependence on chemical composition of the applied filler wires and/or embedded elements, thermal cycle of welding and heat treatment modes was established.

One can see from the data in Tables 2 and 3 that the change of the morphology of liquid eutectic phase distribution and temperature ranges of weld solidification in case of application of silicon-containing wires, causes an increase in primary dendrite dimensions in welds as a result of higher liquid eutectic mobility in the intergranular space and lowering of their formation temperature. Hardness level in this technology variant varies in the range of 12.5–20.1 units. Such a pattern of hardness distribution is due to interaction of alloying elements of the alloy and of filler materials under the temperature–time

TABLE 3. Influence of heat treatment on hardness of D16 alloy welded joints made by consumable electrode using batch-produced Zv1201 filler wire and embedded elements from Zn-containing alloys.

State of base metal and welded joint	Hardness, *HRB*									
	BM	Zv1201+7056 inserts			Zv1201+V96 inserts			Zv1201+V92 inserts		
		Weld	WJ	HAZ	Weld	WJ	HAZ	Weld	WJ	HAZ
After welding and natural ageing	65–67	90–91	61–87	59–65	89–90	61–85	59–65	89–90	62–88	60–65
Welding + artificial ageing		87–90	82–90	58–65	92–92	70–91	59–65	90–93	72–93	63–66
Welding + quenching + artificial ageing	100–102	98–99	100–101	100–102	99–99	100–101	99–102	98–99	100–101	97–102

conditions of consumable-electrode welding [5]. Modulation of the main parameters of welding mode with cycle time of 2.2 ± 0.2 s created the necessary thermo-physical conditions. This is accompanied by improved control of the process of drop transfer from the main wire, producing the appropriate metal pool shape and formation of a dense structure of welds. Such conditions ensure an increased amount of the solid solution, and promote higher density of precipitates of dispersed particles of the hardening phase, that influences the joint hardness.

By their analysis data, a slight increase (5–7%) in the level of hardness of the weld metal and zone of its fusion with the base metal is observed, after artificial ageing of the joints made with batch-produced ZvAK5 and ZvAK12 wires. This is, probably, due to a small number of secondary phase inclusion precipitates, found along the crystallite boundaries in the welds and base metal grains, and influencing the structure strength. In the HAZ, this value grows by only 3–5 units and reaches the base metal level in the naturally aged condition (59–65 units).

Application of embedded elements (from V92, V96 and 7056 alloys) as additional materials also causes an increase of metal hardness level by 2–5 units in different zones of the joint, compared to joints, made by batch-produced wires. The level of hardness value is determined by the amount of zinc in the composition of the respective additional embedded elements (Table 3).

Conducting a full cycle of welded joint heat treatment ensures a more significant increase in hardness value in all the structural zones. Irrespective of silicon presence in the filler wire, its level increases by 25–30% (Tables 2, 3). The greatest effect of hardness increase is observed in the weld. Similar to artificial ageing, hardness value depends on silicon content in the additional filler wires. In the fusion zone, the difference in hardness values is just 1–2 *HB*, and in the heat-affected zone these values are similar.

Hardness level of D16-alloy base metal, which was artificially aged, increases by almost 10% relative to this value in the naturally-aged state, and it is equal to 100–102 *HRB* (Tables 2, 3). Performance of the full cycle of heat treatment of the joints, welded with embedded elements, creates a similar pattern of hardness change. Its level rises by 2–5 *HRB*, compared to joints made with application of silicon-containing filler wires. The hardness effect is determined by the amount of zinc in the additional materials.

Evaluation of Mechanical Properties. During mechanical tests for static tension, fracture of D16-alloy welded joints takes places in the HAZ subzone, where metallographic analysis revealed centres of formation of a network of brittle intermetallic phases located along the grain boundaries, because of grain coagulation. The fracture relief retains tough fracture regions, which is indicative of the mixed mode of joint destruction. In case of application of ZvAK5 and ZvAK12 filler wires, the ultimate strength of welded joints was equal to 186–188 MPa, on average, and that of weld metal was 180–187 MPa. Here, ductility value (bend angle) varied in the range of 27–44 degr. (Table 4). That is, during consumable-electrode welding, favourable conditions are in place for physicochemical interaction of alloying elements and additives of base metal and wires, containing silicon. It additionally expands the amount of eutectic of a balanced composition and improves the structural homogeneity of the welds, both in the weld centre, and on the fusion boundary with the base metal.

Performance of the operation of artificial ageing of welded joints does not cause any essential increase of the yield limit (Table 4). It increases only by 2–3% and remains on the level of 200 MPa, but the bend angle value somewhat decreases to 22–32 degr.

Fracture sites are coarse phase particles and insoluble intermetallics, located along the weld crystallite boundaries or in the zone of its fusion with the base metal. Performance of the operation of full heat treatment ensures an increase of welded joint strength to 282.8–298.2 MPa in specimens made with ZvAK5 and ZvAK12 wires. The joint fracture mode is similar.

Zinc presence in embedded elements from V92, V96 and 7056 alloys promotes an increase of joint strength level, due to its availability in $Mg(Zn_2AlCu)$ and $Mg_3Al_2Zn_3$ secondary phase components [1]. Performance of just the artificial ageing causes a slight increase in the strength of the joints made using embedded elements. Its value is equal to 195.8–198.0 MPa, and ductility is of 22–27 degr. compared to as-welded state (joint strength of 190–200 MPa, that of weld metal of 191–194 MPa, (bend angle) varies from 27 to 36 degr.). Zinc content in embedded elements determines the level of joint strength and ductility (Table 4).

TABLE 4. Influence of technology variants at application of various filler materials for D16 alloy welding and of subsequent heat treatment on the joint mechanical properties.

Filler material grades	Mechanical properties of welded joints in different conditions														
	as-welded*					welding + artificial ageing*					welding + quenching + artificial ageing**				
	σ_t^{WJ}	σ_t^{WM}	α, degr.	Strength factor, *K*		σ_t^{WJ}	σ_t^{WM}	α, degr.	Strength factor, *K*		σ_t^{WJ}	σ_t^{WM}	α, degr.	Strength factor, *K*
	MPa			1	2	MPa			1	2	MPa			1
Zv1201 (base)	193.0	186.0	40	0.79	0.76	198.1	197.6	36	0.64	0.64	301.1	285.6	31	0.69
Zv1201 + ZvAK5	188.0	187.0	44	0.77	0.76	194.7	191.7	32	0.63	0.62	298.2	242.3	21	0.69
Zv1201 + ZvAK12	186.0	180.0	27	0.76	0.73	98.0	190.0	18	0.69	0.69	282.8	243.9	28	0.69
Zv1201 + 7056 alloy	194.0	190.	31	0.79	0.78	201.2	198.0	23	0.69	0.69	296.0	230.4	18	0.69
Zv1201 + V96 alloy	200.0	194.0	36	0.82	0.79	199.0	195.4	27	0.69	0.69	301.4	270.0	23	0.69
Zv1201 + V92 alloy	191.0	190.0	27	0.78	0.78	198.0	195.8	22	0.69	0.69	273.7	189.0	12	0.69

Notes: 1. Average values of strength ($\sigma_{t\ WJ}$, $\sigma_{t\ WM}$) and bend angle (α, degr.) of welded joints by the results of mechanical testing of three specimens. 2. Strength of D16 alloy base metal: after welding and natural ageing, after artificial ageing—310 MPa, after full heat-treatment cycle—340 MPa. 3. *—specimen fracture ran through the base metal in the HAZ. 4. **—specimen fracture ran along the weld axis and along the boundary of its fusion with base metal of D16 alloy. 5. Strength factor (1—welded joint—$K = (\sigma_B^{WJ}/\sigma_B^{bM})$WJ and 2—weld metal—$K = (\sigma_B^{WM}/\sigma_B^{bM})$) is given in comparison with the strength level of D16 alloy base metal in the natural condition, after artificial ageing and full heat-treatment cycle.

The highest strength of welded joints (up to 301.4 MPa) and weld metal (up to 296.0 MPa) is noted at application of V96 alloy. Specimen fracture at mechanical testing runs along the weld axis or boundary of its fusion with the base metal that reflects the dependence of the joint structure on the thermal-cycle effect in welding D16 alloy.

Performance of full heat treatment of joints made using embedded elements, increases the strength level to 273.7–301.4 MPa, and for weld metal to 189.0–270.0 MPa (Table 4). The level of ductility (bend angle) here varies from 12 to 23 degr. Strength increase depends on zinc presence in the filler material composition. In keeping with the data of Refs. [1, 3], weld strengthening can be achieved as a result of formation of dispersed precipitates of metastable η′-phase, the composition of which was determined to be $Mg_4Zn_{13}Al_2$ phase. The observed heterogeneity of excess phase and intermetallic cluster dimensions can be associated with silicon presence in Mg_2Si and $W(Al_xMg_5Cu_6Si_4)$ phases. Under the artificial ageing conditions, they dissolve in the liquid metal and strengthen it, but this increase is small. Zinc presence in the structure of welds, produced using embedded elements, promotes formation of $Mg(Zn_2AlCu)$ and $Mg_3Al_2Zn_3$ secondary phases, which increase the strength level of the joints and weld metal up to 301.4 MPa and 296.0 MPa, respectively. Specimen fracture under tension also occurs along the weld axis or the boundary of its fusion with the base metal. The fracture sites are phase particles, which do not dissolve in liquid aluminium, but form centres of extended intermetallic inclusions by coagulation. Presence of tough cells on fracture relief, alongside the quasi-cleavage elements, may be indicative of stress localization and concentration of ductile shear in individual structural regions, in keeping with the conclusions of work [2]. Thus, both the operation of artificial ageing and full heat-treatment cycle can be performed in order to improve the mechanical properties of D16 alloy joints in consumable electrode welding.

Their effectiveness is determined by the volume fraction of base metal phase particles and amount of alloying elements and additives at weld modifying. The degree of influence on the structure and mechanical properties depends on their amount, their ratio in the welded-joint zones and segregation along the boundaries of weld crystallites and base metal grains.

Moreover, it should be also noted that welded structure fabrication in the shop does not always provide favourable conditions for heat treatment performance. The above-mentioned problem arises in the case of absence of the necessary thermal furnaces, and also at large overall dimensions and considerable weight of individual structural elements, *etc.*, that is when the full heat treatment cycle cannot be implemented under the production conditions.

In this case, the operation of artificial ageing can be applied. In case of absence of the mentioned production difficulties for performance of heat treatment of welded parts or components from D16 alloy, application of a full heat-treatment cycle of welded structural elements is more rational. At its realization, a more favourable structure of welded joints and optimal values of mechanical properties, namely, strength and ductility are achieved.

4. CONCLUSIONS

1. The nature of structural transformations taking place in D16 alloy during heat treatment, namely, artificial ageing or full cycle (quenching and artificial ageing), was evaluated. Their effectiveness is determined by the size of volume fractions of base metal phase particles and amount of alloying elements and additives, applied for modifying the welds made by consumable electrode. The extent of impact on the structure and mechanical properties is determined by their amount in the filler metal, segregation along the boundaries of weld crystallites and base metal grains. Weld microstructure is homogeneous, and consists of solid solution and finely dispersed inclusions of $CuAl_2$ phase and eutectic of $(\alpha + CuAl_2)$ type. Alongside the solid solution, up to seven diverse phase inclusions are found in the structure, their combination influencing the level of welded joint mechanical properties.
2. The level of joint strength depends on the type of D16 alloy heat treatment, and it is determined by the geometrical dimensions and morphology of phase precipitates in the structure. Artificial ageing of joints made with batch-produced ZvAK5 and ZvAK12 wires results in their strength increase by 2–3% (190.0–195.8 MPa). Bend angle value is equal to 22–32 degr., which is due to transition of brittle intermetallic phases into the aluminium solid solution. Silicon presence in the composition of Mg_2Si and $Al_xMg_5Cu_6Si_4$ phases only slightly strengthens the joint. Conducting full cycle of welded-joint heat treatment raises the strength value largely (282.8–298.2 MPa), that is by 20–27% higher than under the conditions of artificial ageing. Specimen fracture runs along the weld axis or the boundary of its fusion with the base metal.
3. A similar regularity of strength increase is observed in joints welded with embedded elements. After artificial ageing, the strength level is equal to 195.8–198.0 MPa, and after the full cycle, it is of 273.7–270.0 MPa, depending on chemical composition and zinc content in the welds when using V92 and 7056 alloys. The greatest effect of strength increase in the joints (up to 301.4 MPa) and weld metal (up to 296.0 MPa) is observed at application of V96 alloy. Probably, this is promoted by formation of $Mg(Zn_2AlCu)$ and $Mg_3Al_2Zn_3$ secondary-phase compounds during weld solidification. Under the conditions of tension, the joints fail along the weld axis or the boundary of its fusion

with base metal.

4. It was confirmed that performance of heat treatment of D16 alloy joints made by consumable electrode, ensures an increase of hardness level, and it is determined by the volume of the respective transformations in different structural zones. After artificial ageing of the joints produced with ZvAK5 and ZvAK12 wires, hardness rises by 5–7% compared to as-welded state, and for those produced using embedded elements, it is 3–5% higher. The amount of silicon or zinc in the composition of the applied filler materials determines the extent of the effect of welded joint hardening. Performance of full heat treatment of the joint further increases their hardness by 2–5 *HRB*.

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