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EFFECT OF HEAT TREATMENT ON THE STRUCTURE AND MECHANICAL PROPERTIES OF SHEET ALUMINIUM ALLOY V1341 AND ITS WELDED JOINTS PRODUCED BY TIG WELDING

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The paper gives the results of studying the effect of various heat treatment operations on the structure and mechanical properties of the base metal and welded joints of sheet aluminium alloy of V1341 grade 1.2 mm thick, produced by manual nonconsumable electrode argon-arc welding. The dependence is established between the structural state of the metal of welded joints of this alloy on the kind of heat treatment that affects the level of strength and ductility. A significant effect of improvement of the structure and mechanical properties is achieved, when conducting complete heat treatment, which includes quenching and artificial ageing of the alloy and its joints. Compared to artificial ageing modes, this kind of heat treatment allows producing a stable metal structure, characterized by smaller dimensions of phase precipitates and inclusions that promotes increase of the strength level, under the condition of preservation of the ductility values. 8 Ref., 2 Tables, 4 Figures.

Keywords: aluminium alloy, manual nonconsumable electrode argon-arc welding, filler wire, welded joints, heat treatment, structure, mechanical properties, investigations

V1341 alloy of Al–Mg–Si–Cu–Fe alloying system belongs to the class of aluminium alloys, which are sensitive to process heating. High-temperature heating of this alloy in welding changes the base metal structure, violating its uniformity, and lowers its strength. Characteristic structural zones, such as the weld, fusion zone and HAZ, are formed. This is affected by the temperature conditions of heating in individual regions, and the features of the local structural transformations depend on the processes of diffusion of alloying elements and impurities, present in this alloy composition. The volumes of precipitation or dissolution of phases which form here, are determined by the duration of temperature gradient staying in the base metal regions relative to the weld axis, i.e. welding speed. The operation of the joint heat treatment is conducted to improve their structure and properties [1–3]. This is due to the need to ensure in manufacture of complex-shaped stamped elements the appropriate level of mechanical properties of aviation parts and components — suspended tanks, containers and other products. Such blanks are joined predominantly by manual argon-arc welding. It should be noted that the kind of heat treatment is selected, depending on welded structure purpose, as well as operating requirements to the products, exposed to complex conditions of alternating loads in service [4].

Heat treatment kinds include the following operations: quenching, natural or artificial ageing. Their temperature-time modes allow regulating the structure state by reproducing the respective phase transformations and achieving certain morphology of the structural components, the dimensions and density of which promote an increase of the strength level.

The process of metal quenching (solid solution treatment) envisages appearance of an equilibrium state in the structure at a high temperature of heating (0.85−0.90 T_m). In this case, the alloying elements and excess phases, included into the alloy composition, dissolve completely or partially. The time of metal soaking at the appropriate temperature, together with cooling to room temperature, ensure the conditions of solid solution oversaturation by alloying elements and point defects up to the appropriate concentrations, characteristic for the selected quenching temperature [3]. Dispersed dimensions of the structural components can be fixed at abrupt cooling of the alloy from the quenching temperature. Precipitates of Guinier–Preston (GP) zones are the first to form. They are in metastable equilibrium with the solid solution that promotes improvement of the alloy mechanical properties. It is known [2] that the degree of strengthening of V1341 alloy during ageing is directly related to the volume fraction of Mg_2Si phase, which goes into the solid solution at heating.

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Metal staying under atmospheric conditions after quenching («natural ageing») promotes slow development of phase transformations, realization of which in the future stabilizes the structural state and ensures a certain level of mechanical properties. The structure becomes completely stable after 10–15 days.

Maximum values of strength and yield limit characteristics of aluminium alloys are usually achieved at application of artificial ageing operation [1]. If such an operation is performed one hour after quenching, then a slight lowering of the above-mentioned strength characteristics and increase of the ductility value are observed in the metal. Increase of the time interval between performance of the operations of quenching and artificial ageing does not allow achieving the required level of alloying element concentration, and, hence, of the respective mechanical properties. Therefore, the objective of this work is determination of the effectiveness of the mentioned heat treatment operations, based on studying the structure and mechanical properties of V1341 alloy in the condition of natural ageing (T) and of its welded joints, made by manual nonconsumable electrode welding.

Investigation procedure. Sheet blanks of V1341T alloy 1.2 mm thick were treated by the traditional preparation procedure before welding. The blank end face was cleaned mechanically by a scraper to not less than 0.1 mm depth. Manual arc welding of butt welds was performed along the rolling direction of sheet semi-finished products by different polarity current of a sinusoidal shape, using Fronius Company equipment. The joint was produced using 1.2 mm filler wire of Sv1217 grade, which ensures a high coefficient of structural strength of the joints [6].

Weld quality was controlled [7] by appearance of the technological reinforcement and X-ray examination results (GOST 7512–89), obtained in RAP-150/300 unit. Weld metal density was determined in «Densitometer» instrument. Control results allowed selection of optimum welding modes, at which no coarse defects form, of the type of cracks, lacks of penetration, pores, etc. As shown by analysis of welded butt joints, the highest quality welds were produced in the following mode: I_w = 54–56 A, U_a =11.0–12.4 V.

Heat treatment of test samples of V1341 alloy base metal and its welded joints were conducted by technology variants, the most widely accepted in production, namely, by artificial ageing in the following mode: T = 190 ± 5 °C for 12 h, as well as by performance of complete heat treatment, which included the quenching operation (T = 525 ± 5 °C for 30 min) with cooling in water of room temperature for fixation of dispersed dimensions of the solid solution. Further artificial ageing was performed by the above mode. Part of the joint samples was studied in as-welded state.

Quantitative assessment of the nature of the change of strength and ductility values of the base metal and welded joints of V1341 alloy, depending on the studied heat treatment modes, were determined in an all-purpose TsD-4 machine with 2t scale by the results of mechanical standard testing under the conditions of tension. Flat samples of XIII type (GOST 6996–66) were used, in order to establish the strength values of the base metal and the joints. Welded joint samples had process reinforcement on the face surface of the butt joint and the weld root. Sample loading at testing was uniform over its entire working part, in keeping with the requirements of GOST 1497–84. Deformability of the base metal and its welded joints was analyzed, using a technological characteristic — bend angle (α), which was achieved under the conditions of three-point bending with application of loading from the weld root side after its scraping.

For optimization of the modes of welding V1341 alloy and assessment of the effect of heat treatment of its welded joints, their macrostructural features were studied on sections, cut out transversely to the weld axis, after chemical etching of the samples in the respective solution. The microstructural features of the base metal and different regions of the welds and HAZ were revealed by electrolytical polishing of the welds in the following solution: 930 ml CH_3COOH + 70 ml $HClO_4$.

Investigation results. Results of studying the microstructural features of V1341 alloy base metal at different heat treatment operations are given in Figure 1. In keeping with the data of metallographic analysis, it was found that the alloy microstructure in the «quenching + artificial ageing» state consists of saturated solid solution, phase precipitates and coarse inclusions of insoluble intermetallics (Figure 1, *a*). In keeping with the state diagram of Al–Mg–Si–Cu–Fe system, both binary phases (Mg_2Si, $FeAl_3$, Mg_5Al_8), and ternary phases — $SiCuAl_2$, $CuFeAl_5$, $CuMnAl_2$, $FeSiAl_5$, $FeMg_3Si_6$, can be in equilibrium with the solid solution. After artificial ageing, an increase of the quantity of phase precipitates on the grain boundaries is observed in the structure (Figure 1, *b*). The extent of insoluble intermetallic phases is also increased due to their combination, that causes an increase of base metal strength level (Table 1). Metastable equilibrium relative to the solid solution results in improvement during artificial ageing of all the mechanical properties of V1341T alloy, including the ductility values. Performance of complete heat treatment which includes «quenching + artificial ageing» leads to formation of structural components with smaller geometrical dimensions (Figure 1, *c*). In keeping with the data of [2], presence of a small quantity of copper additives (0.3 %) in the alloy, promotes limitation of precipitates of Guinier–Preston (GP) zones in the alloy structure.

Let us consider the effect of V1341 alloy structural state after different kinds of heat treatment on the nature of the change of mechanical properties (Table 1). Analysis of the obtained results shows that the strength and yield limit of the alloy in the «quench-

Figure 1. Microstructure (×320) of base metal of V1341 alloy in the state after quenching and natural ageing (*a*), after artificial ageing (*b*) and after complete heat treatment (quenching and artificial ageing) (*c*)

Table 1. Effect of the kinds of heat treatment on mechanical properties of base metal of V1341 alloy

State	σ_y, MPa	$\sigma_{0.2}$, MPa	δ, %	α, deg
Quenching + natural ageing	250.1–250.8 / 250.5	187.0–188.41 / 187.6	18.7–19.0 / 18.9	180
Artificial ageing	333.8–337.3 / 335.7	310.1–316.4 / 313.3	8.5–10.0 / 9.5	180
Quenching + artificial ageing	320.1–332.1 / 332.1	281.8–282.2 / 282.0	10.4–11.4 / 10.7	136–180 / 158

ing + natural ageing» state (T) are equal to 250.5 and 187.6 MPa, respectively. The relative elongation here is 18.9 %, and bend angle is 180°.

After performance of the operation of the alloy artificial ageing, an increase of the strength level and yield limit up to the values of 335.7 and 313.3 MPa is observed, but the relative elongation value decreases to 9.5 %. Deformability (bend angle) of the metal does not change (180°).

In the case of conducting the complete cycle of heat treatment (quenching + artificial ageing) a slight lowering (to 321.1 and 282.2 MPa) of the level of strength and yield is observed in the alloy. The relative elongation value is equal to 10.7 %, and the bend angle decreases to 158°. The nature of the change of base metal mechanical properties can be related to the features of decomposition of oversaturated solid solution under the certain conditions of inclusion precipitation along the grains boundaries, as well as of highly dispersed hardening of the metal, which ensure the required complex of mechanical values of this alloy [8].

Metallographic analysis of the macrostructure of V1341T alloy joints in different zones: weld, zone of its fusion with the base metal and HAZ (Figure 2) showed that the welds are characterized by high quality, as the structure in the weld bulk is uniform and consists of fine dendrites, while coarse defects are absent. In the near-weld zone in as-welded joints we can see three regions of different degree of etching that reflects the impact of the welding thermal cycle on the metal structure. After artificial ageing of welded joint samples, this zone has a lighter colour of the surface along its entire length, which is in contrast with the weld surface. Performance of quenching and artificial ageing (complete cycle of the joint heat treatment) leads to greater colour contrast of the HAZ metal that is indicative of the change of structural component parameters (grain size, interlayers between them, phase inclusions, etc.) in these regions under the impact of process heating.

Performance of the process of arc welding of V1341 alloy changes the microstructural pattern in the joint zone, compared to base metal structure (Figure 3). The

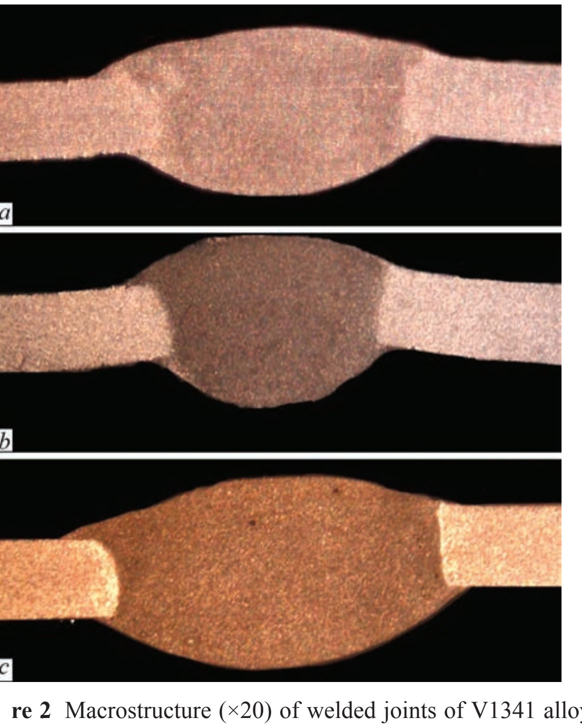

Figure 2. Macrostructure (×20) of welded joints of V1341 alloy of Al–Mg–Cu–Si alloying system after welding (*a*), artificial ageing (*b*) and complete heat treatment cycle (*c*)

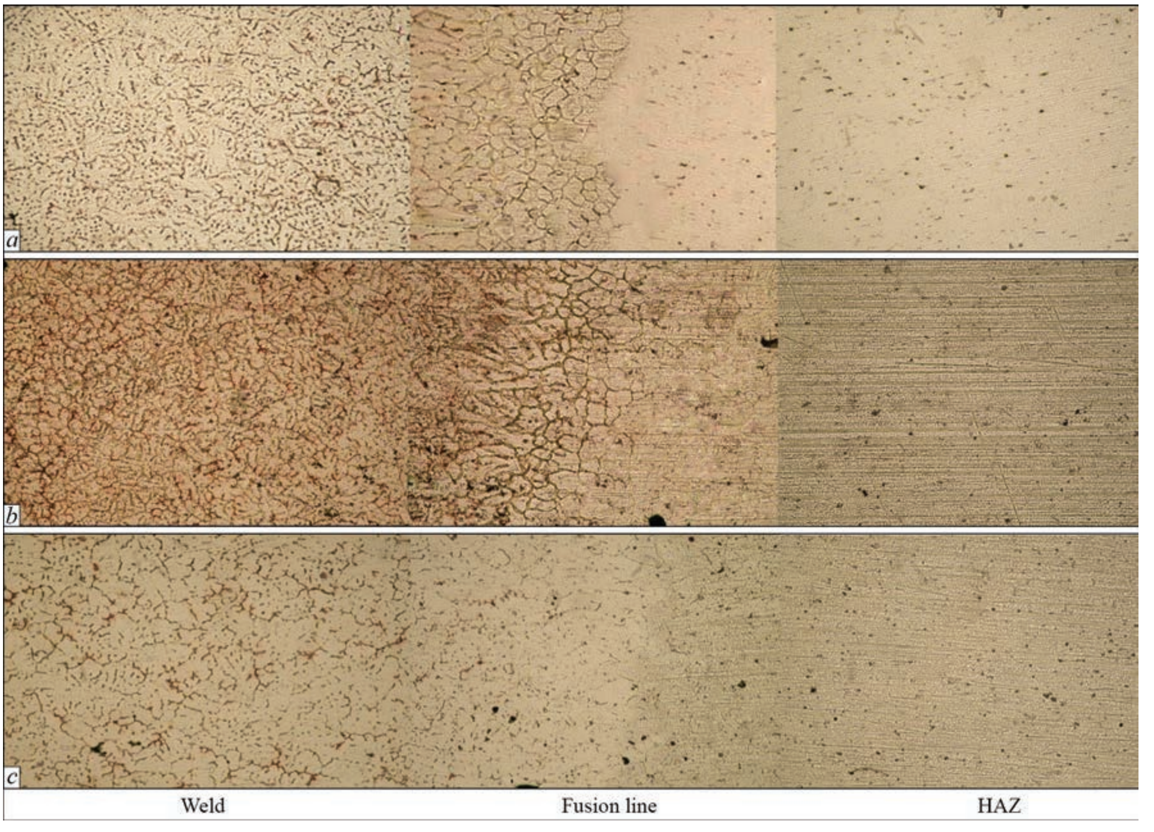

Figure 3 Microstructure (×320) of welded joints of V1341T alloy produced by manual process after welding (*a*), artificial ageing (*b*) and complete heat treatment (*c*)

nature of precipitation or dissolution of phases, which form here in different base metal regions relative to weld axis, and their volumes are due to the temperature gradient in the weld, fusion zone and HAZ. Their analysis is indicative of the fact that the impact of the welding thermal cycle results in decomposition of oversaturated solid solution. It is accompanied by dissolution of the earlier formed strengthening phases, precipitation of new phases and coagulation of inclusions of insoluble intermetallic phases. Metal boundary areas are enriched in alloying elements, and the bulk is depleted in them.

Weld structure has a characteristic phase arrangement and consists of fine dendrites. No coarse defects or discontinuities were observed in the weld bulk. In keeping with the data of weld microstructure analysis, the crystallites differ by the shape and direction. They have a typical cellular-dendritic structure characteristic for the cast state of the metal (Figure 3, *a*). A considerable quantity of metastable phases uniformly arranged over the cross-section, is observed between the crystallites. This is due to the complex nature of alloying, i.e. presence of various main alloying elements and impurities. They differ by their size and shape. Thin eutectic interlayers form along the crystallite boundaries. Enlargement of intermetallic phases due to their combining is also observed.

Near the fusion line, where the first stage of solidification occurs, the structure is predominantly fine-crystalline. The processes of heat removal and solidification overcooling, which proceed in the weld pool during metal cooling and its solidification, promote formation of the zone of columnar crystallites, which are oriented predominantly in the direction of the action of melting isotherm vector. Presence of partially-melted grain boundaries is observed from the base metal side.

Weld microstructure on the boundary of its fusion with the base metal, is characterized by the presence of partially-melted grain boundaries, which formed under the conditions of heating in welding. It is accompanied by thickening of the boundaries, as a result of contact melting of the grains between each other and Mg_2Si eutectic phase, which is located along the grain boundaries, under the welding conditions. Structure coarsening is observed in the HAZ metal, which is due to increase of the grain dimensions and coagulation of insoluble phase inclusions.

Decomposition of oversaturated solid solution takes place in the fusion zone from the base metal side under the conditions of welding thermal cycle. It is accompanied by the processes of simultaneous precipitation and dissolution of earlier formed strengthening phases, as well as coagulation of insoluble intermetallic phases, which penetrate into the alloy structure at the stage of metallurgical production [3]. Interaction of near-boundary intermetallic inclusions with the solid solution leads to appearance of liquid interlayers of low-melting eutectic along the grain boundaries. Structural transformations, complete or partial lower-

Tb le 2 Mechanical properties of welded joints of V1341T alloy (δ = 1.2 mm) after manual argon-arc welding and different kinds of heat treatment

Welded joint state after performance of	σ_y, MPa	$\sigma_{0.2}$, MPa	δ, %	α, deg	$K = \sigma_y^{33}/\sigma_y^{BM}$
Welding	208.2–208.0 / 208.7	131.6–147.8 / 147.5	4.6–5.4 / 5.1	45–66 / 56	0.83
Artificial ageing	248.4–274.0 / 257.6	198.3–231.7 / 215.5	1.4–2.8 / 1.9	20–46 / 30	0.77
Quenching and artificial ageing	297.0–301.9 / 299.6	213.8–265.5 / 241.5	6.4–7.1 / 6.9	20–50 / 32	0.93

ing of the effect of strengthening after natural ageing, local annealing and hardening of individual regions of this joint zone take place in the HAZ under the impact of the welding thermal cycle.

After artificial ageing of welded joint samples, a change is observed in the weld structure, which is the result of decomposition of the solid solution, precipitation of additional phases and their dispersion hardening (Figure 3, *b*). It leads to increase of phase density, and their volume fraction that is accompanied by thickening of the boundaries of weld crystallites and grains in the HAZ, as a result of their possible contact melting between each other and Mg_2Si eutectic phase, as it is located near their boundaries. Coarsening of the grains and coagulation of insoluble phase inclusions occur in the HAZ metal that is characteristic for all the aluminium alloys after arc welding [5].

Conducting a complete heat treatment cycle leads to formation of a more uniform nature of distribution of phase precipitates from the matrix (Figure 3, *c*). Here, the shape and the dimensions of the phases change both near the weld crystallites and base metal grains. They are more dispersed. This is due to the fast fixing of the structural components after quenching, the shape and dispersed sizes of which are preserved at further artificial ageing. In addition, a thickening of the boundaries of the crystallites and grains is observed, in particular, in the zone of weld fusion with the base metal, but the thickness dimensions are smaller than in the structure after artificial ageing.

The results of testing samples of welded joints from V1341T alloy under the conditions of uniaxial tension and three-point bending show that the level of mechanical properties directly depends on the arrangement of the structural components, as a result of structural transformations, running in the metal during welding and heat treatment (Table 2).

Compared to base metal values in a similar heat-treated state, the level of mechanical characteristics of the joints is somewhat lower. Their strength factor in as-welded samples, which were tested with a bead and technological reinforcement of the weld, amounts to 0.83 % on average, relative to base metal strength level, and is equal to 208.7 MPa on average. The yield limit value is on the level of 147.5 MPa. Ductility values are as follows: relative elongation 5.1 %, bend angle — 56°. Failure of samples of such joints occurs in the section of base metal HAZ at the distance of 4–5 mm from the fusion line (Figure 4, *a*).

Increase of the values of strength and yield level up to 257.6 and 215.5 MPa, respectively, is observed in the welded joints after artificial ageing. The strength factor of the joints can reach 0.77 on average. Relative elongation value is equal to 1.9 % that is almost 2–3 times less than that of the base metal in a similar state. The value of bend angle of the joints is 30° on average. Fracture of such welded joints occurs both along the line of fusion of the weld with the base metal, and in the HAZ at 5 mm distance from the boundary (Figure 4, *b*). The first can be caused by metal overheating during performance of manual welding; the second — by a considerable quantity of phases, which precipitate from the solid solution under the conditions of artificial ageing, as well as coagulation of coarse particles of the intermetallic phases. Together they form in the zone of weld fusion with the base metal a continuous net around the grains (Figure 3, *b*). Its presence causes an abrupt lowering of the ductility values (Table 2). The noted fact should be taken into account during selection of the operations of heat treatment of welded joints from V1341T alloy.

After the complete heat treatment cycle (quenching + artificial ageing) the strength of welded joints is equal to almost 300 MPa, and the yield limit is 265.5 MPa. The strength factor of such joints is equal to 0.93 of that of the base metal. The value of relative elongation, although it is two times smaller than in the base metal, still remains on the level of 6.9 %. Bend angle is 32°. The nature of fracture of the samples is the same as in the previous case, i.e. nonuniform (Figure 4, *c*). Some samples break along the fusion line, and others — in the regions of base metal in the HAZ, where annealing of welded joint metal occurs during the thermal cycle of welding. The established fact can also be related both to base metal quality, and to the stability of manual welding performance.

Thus, different kinds of heat treatment ambiguously affect the state of the metal of V1341T alloy welded joints. The greatest effect is produced by the heat treatment technology, which includes quenching and artificial ageing of the alloy joints. Its mode allows obtaining the structure of the metal, with which the strength level is increased compared to modes of only the artificial ageing. This is due to the dimensions of phase precipitates and their density in the metal that

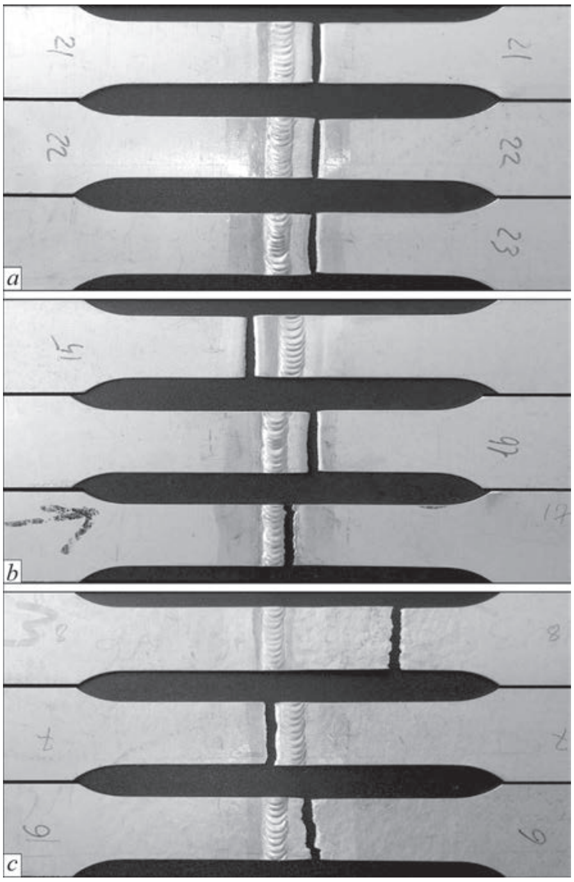

Figure 4 Nature of fracture of welded joints of V1341T alloy, produced by manual nonconsumable electrode argon-arc welding, depending on the kind of heat treatment: *a* — after welding; *b* — after artificial ageing; *c* — after complete heat treatment cycle

affects the stress level in the structure. Presence of finer phases, with a uniform nature of arrangement in the bulk near the weld crystallites and base metal grains, promotes uniform deformation and does not cause stress localization on their boundaries. Thus, the complete heat treatment cycle is an effective means of improvement of the structure and mechanical properties of V1341T alloy and its welded joints, including the ductility values: relative elongation and bend angle.

Conclusions

1. Results of investigation of the structure of V1341 alloy 1.2 mm thick show that the metal sensitivity to the kinds of heat treatment determines the level of its mechanical properties.

2. It is found that sound weld formation occurs at application of filler wire of Sv1217 grade during manual nonconsumable electrode welding of V1341T alloy. The level of their strength and yield values after welding is equal to 208.7 and 147.5 MPa, respectively. Relative elongation value is 5.1 %. The strength factor is equal to 0.83 relative to base metal values in the state of quenching and natural ageing.

3. Performance of artificial ageing of samples of V1341T alloy welded joints increases the level of strength and yield limit of the joints by 60–70 MPa on average, and they are equal to 257.6 and 215.5 MPa, respectively. Relative elongation value is 1.9 % that is almost 5 times smaller than that of the base metal in a similar state. The value of bend angle of the welded joints is equal to 30° on average. This is related to a large quantity of phases, precipitating along the grain boundaries under the artificial ageing conditions, as well as enlargement (coagulation) of coarse particles of insoluble intermetallic phases. Together, they form a continuous net around the grains and lower the ductility values. Fracture of welded joint samples occurs both on the line of weld fusion with the base metal, and in the HAZ at 5 mm distance from it.

4. Performance of a complete cycle of heat treatment of V1341T alloy welded joints promotes an increase of the strength level by 80–90 MPa, compared to as-welded state. It is on average equal to 299.6 MPa. The yield limit value is 241.5 MPa. Values of ductility characteristics (relative elongation and bend angle) are equal to 6.9 % and 32 %, respectively.

5. It is found that in order to ensure the appropriate level of mechanical properties of welded joints of V1341T alloy in structures under production conditions it is rational to apply the complete cycle of heat treatment, which includes quenching and artificial aging. Its modes do not lead to the conditions, under which coarse changes of the structure and embrittlement of the metal take place, particularly in the zone of the weld fusion with the base metal.

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