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METALLURGICAL PROCESSES IN THE WELD METAL IN ELECTRON BEAM WELDING OF 01570 ALUMINIUM ALLOY

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ABSTRACT

Scandium and zirconium content was determined in different areas of welded joints of stamped semi-finished products of 01570 aluminium alloy produced by electron beam welding. It was found that dissolution of not only secondary, but also of a part of primary $Al_3(Sc, Zr)$ intermetallics, contained in the base metal, takes place in the weld pool. The quantity of scandium dissolved in the liquid metal, is determined by the time of the pool existence. Further on, scandium is completely or partially fixed in an oversaturated solid solution, depending on the rate of hardening during the weld metal cooling. At 0.10–0.12 % concentration of scandium dissolved in the weld pool, its complete transition into an oversaturated solid solution ensures hardening at not less than $5 \cdot 10^2$ °C/s rate. It is shown that approximately 50 % of scandium contained in 01570 alloy, participates in hardening of stamped semi-finished products. The remaining scandium is present in the composition of primary intermetallics.

KEYWORDS: electron beam welding; aluminium alloy; hardening; artificial aging; intermetallics

INTRODUCTION

The 01570 alloy is the most strength among other thermally non-strengthened wrought aluminium alloys of Al–Mg system [1]. By the level of strength properties, wrought semi-finished products of 01570 alloy in the annealed state approach the level of properties of wrought semi-finished products of thermally strengthened aluminium alloys in the state after hardening and artificial aging. It should be noted that heat treatment in the form of annealing for 01570 alloy is strengthening. The chemical composition of the alloy is given in Table 1. In casting of the alloy ingots, a fixation of scandium in an oversaturated solid solution, i.e., hardening occurs. At a subsequent annealing, a decomposition of an oversaturated solid solution of scandium in aluminium with the precipitation of secondary strengthening fine-dispersed particles of Al_3Sc phase occurs. In this connection, as far as concerns 01570 alloy, annealing will be further on called artificial aging. Both for alloys of Al–Sc and Al–Mg–Sc systems in general, as well as for 01570 alloy, in particular, artificial aging at 350 °C of 1 h duration provides the highest increase in strength properties [1, 2]. This heat treatment mode appeared to be better to increase the strength of welded joints of semi-finished products of 01570 alloy [3]. Artificial aging of welded joints produced by electron beam welding (EBW) improves hardness of the weld metal above the level of hardness of the base metal of stamped semi-finished products, and ruptured specimens cut out from aged welded joints are destroyed over the base metal outside the heat-affected zone. This fact gave reason to assume that with an artificial aging in the weld metal, a higher quantity of fine-dispersed secondary Al_3Sc intermetallics precipitated than initially in the base metal.

To form this excess quantity of particles, three conditions should be fulfilled.

First, an additional scandium is required, that has not previously participated in strengthening of the metal. This scandium is formed in the metal at the stage of producing ingots in the form of primary Al_3Sc precipitates.

Secondly, along with a complete dissolution of secondary intermetallics in the weld pool metal, it is necessary to dissolve primary intermetallics at least partially. Due to the fact that after artificial aging, the hardness of the weld metal becomes higher than the hardness of the base metal, such dissolution takes place. It is important to note that the greatest increase in hardness (i.e., more full dissolution of primary intermetallics) occurs at a low welding speed, when the

Table 1. Chemical composition of 01570 alloy (GOST 4784–2019), wt.%

Al	Mg	Mn	Sc	Zr	Ti	Si	Fe	Cu	Zn
Base	5.3–6.3	0.2–0.6	0.17–0.27	0.05–0.15	0.01–0.05	<0.2	<0.3	<0.1	<0.1

time of staying the metal in the liquid state in the area of exposure to the electron beam increases [4].

Third, during cooling of the weld metal dissolved in a liquid metal, scandium should be fixed in a solid oversaturated solution. The complete transition of scandium from the melt into an oversaturated solid solution grows with an increase in the rate of hardening [5]. And in EBW of 01570 alloy, it was found that a decrease in welding speed from 16.8 to 2.8 mm/s and, accordingly, reduction in the rate of hardening from $1\cdot10^4$ to $5\cdot10^2$ °C/s does not decrease, but on the contrary increases the hardness of the weld metal. Therefore, it can be assumed that all or almost all scandium, dissolved in a liquid weld pool metal transfers into a solid solution and further on, during aging, it is released in the form of secondary Al_3Sc intermetallics.

The main factor that restrains the widespread use of aluminium-magnesium alloys with scandium is a high cost of scandium. To reduce the consumption of scandium while maintaining high service characteristics, in aluminium-magnesium alloys, zirconium is introduced. Zirconium is introduced into 01570 metal together with scandium. It dissolves in Al_3Sc intermetallic, replacing atoms of scandium, maintaining and stabilizing its properties [6]. In alloys of Al-Mg system, the optimal content of scandium and zirconium is considered to be 0.22–0.24 and 0.10–0.12 %, respectively. If the specified content is elevated, the excess scandium and zirconium in the alloy are in the form of primary $A1_3$(Sc, Zr) intermetallics, deteriorating the service characteristics of the alloy [7]. For example, in Al–Mg–Sc–Zr alloy at 77 K, primary $A1_3$(Sc, Zr) phases are responsible for arising of cavities and cracks on their interface with a matrix at cryogenic temperature [8]. At a decrease in the specified content, the possibilities of scandium and zirconium are not fully used.

Concerning quantities of these primary intermetallics, the literature gives contradicting data. Previously, the developers of 01570 alloy wrote that the bulk part of scandium remains in an oversaturated solid solution [1, 9] (from this part, at a subsequent thermomechanical treatment, strengthening secondary intermetallics Al_3Sc are formed), and some negligible part of it is precipitated from the melt in the form of relatively large primary intermetallics [10]. In [11] it is asserted that to form a strengthening phase (secondary intermetallics), 50 % of scandium and zirconium is spent, which is introduced into 01570 alloy. The rest of these elements are contained in primary intermetallics.

The aim of the work is to study the features of metallurgical processes occurring in the weld pool in EBW of 01570 alloy, determining the quantity of scandium and zirconium, which goes to the formation of secondary intermetallics in the weld metal and the minimum rate of hardening required for a complete transition of scandium into an oversaturated solid solution during cooling of the weld.

RESEARCH METHODS AND EQUIPMENT

The studies were conducted on the plates of 01570 alloy with a thickness of 30 mm. The plates were welded in the electron beam welding installation UL-209M with ELA 60/60 power source at an accelerating voltage of 60 kV.

On cross-sections with the help of Rockwell device, the hardness of the weld metal and near-weld area was measured. The measurements were carried out during loading on a steel ball of 600 N on a scale B. The mechanical properties of the weld metal were determined by the rupture test of standard cylindrical specimens with the diameter of working part being 4.0 mm and clamps of 9.0 mm diameter.

The test specimens were cut out from the weld metal along the welding direction so that the working parts of the specimens and the adjacent areas consisted of the weld metal. The scheme of cutting out specimens is shown in Figure 1.

The microstructure of the specimens was investigated on transverse sections with the use of the electron microscope Carl Zeiss Sigma 300 at an accelerated voltage of 15 kV.

To determine the chemical composition of different areas of the base metal, weld and intermetallic particles, X-ray spectral microanalyzer Oxford Instruments XMAX-350 (attached analyzer PEM Carl Zeiss Sigma 300) and software for calculating results were used.

EXPERIMENTAL INVESTIGATIONS AND RESULTS

The plates of stamped semi-finished products of 01570 alloy were welded in the lateral position using a horizontal beam. The welding modes are given in Table 2. As the beam scanning amplitude increases

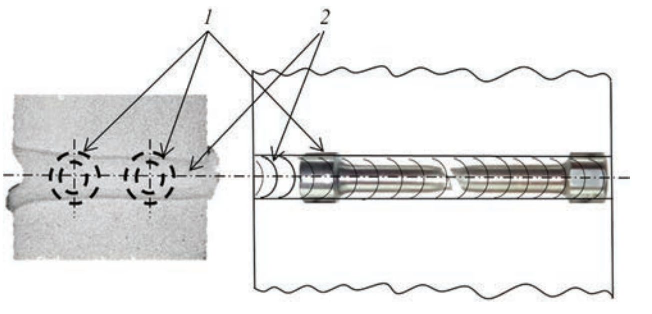

Figure 1. Scheme of cutting out specimens for tensile tests of weld metal: *1* — specimens; *2* — weld

Table 2. EBW modes for welding plates of 1570 alloy of 30 mm thickness

Welding mode	U_b, kV	v_w, mm/s	I_b, mA	Amplitude of beam scanning, mm	Weld width, mm	Rate of hardening of weld metal, °C/s
1	60	2.8	95	1.5	3.5	$5\cdot10^2$
2		16.8	260	Same	Same	$1\cdot10^4$
3		2.8	130	4.0	7.0	Was not measured
4		6.0	220	Same	Same	Same
5		12.0	310	»	»	»
6		16.8	350	»	»	»

from 1.5 to 4.0 mm, the width of the weld increased from 3.5 to 7.0 mm (Figure 2).

For measurements of hardness and mechanical tests after welding, the plates of 01570 alloy were artificially aged at a temperature of 350 °C during 1 h.

The results of measuring hardness of welded joints showed that for all the studied welding modes, the hardness of the weld metal is by 2–6 *HRB* units higher than the hardness of the base metal (Figure 3). The highest hardness (about 96 *HRB*) is in the narrow welds produced at a welding speed of 2.8 mm/s (mode 1). In the case of an increase in the width of the weld from 3.5 to 7.0 mm (mode 3), its hardness is reduced to 91–92 *HRB*. The hardness of the weld metal produced at a welding speed of 16.8 mm/s (modes 2 and 6) is almost independent of their width and is about 93 *HRB*.

Figure 4 shows intermetallics in the base metal (*a*) and in the metal of welds, produced at a speed of 16.8 mm/s (*b*) and 2.8 mm/s (*c*). On the photos against the backdrop of the dark matrix, light, apparently, primary intermetallics are seen, containing scandium and zirconium with the size from 1.0 to 15.0 μm. The inclusions of a rounded shape (Figure 4, *d*, *e*) or in the form of irregular polyhedra (Figure 4, *f*) are encountered. Their chemical composition is wt.%: Al — 60–62, Sc — 21–22, Zr — 17–18.

Fine (1–3 μm) primary intermetallics are distributed in the matrix relatively uniformly, and larger ones (5–15 μm) are chaotic.

At magnifications ×500 and ×1800, it is impossible to detect nanosized secondary $A1_3$(Sc, Zr) intermetallics, which are contained in the base metal. Therefore, the quantity of scandium and zirconium contained in

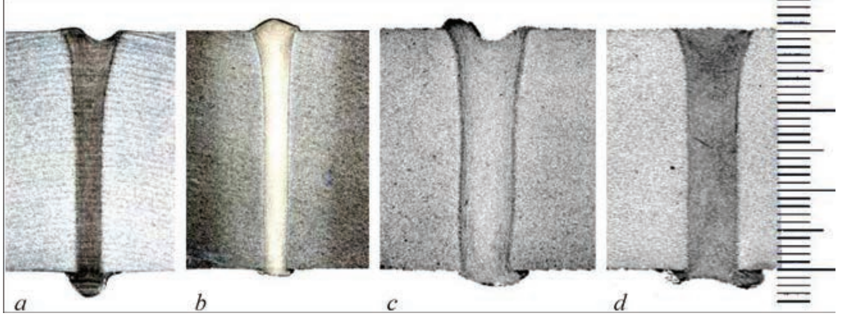

Figure 2. Transverse macrosections of welded joints of plates of stamped semi-finished product of 01570 alloy with a thickness of 30 mm: *a* — mode 1; *b* — 2; *c* — 3; *d* — 6

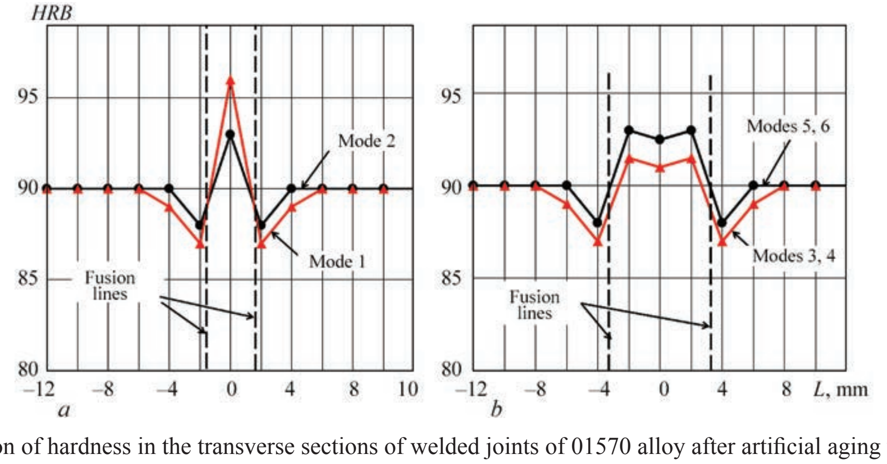

Figure 3. Distribution of hardness in the transverse sections of welded joints of 01570 alloy after artificial aging with an amplitude of electron beam scanning of 1.5 mm (*a*) and 4.0 mm (*b*)

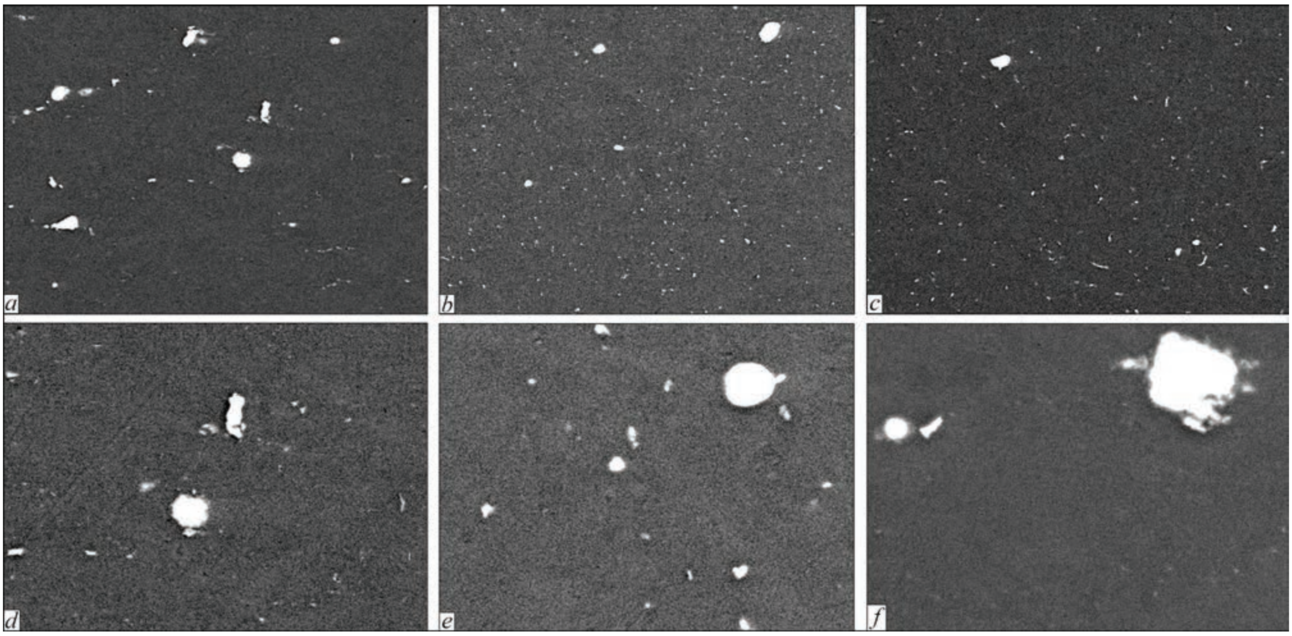

Figure 4. $A1_3$(Sc, Zr) intermetallics in the base metal of 01570 alloy (*a*, *d*) and in the weld metal in EBW on the mode 2 (*b*, *e*) and on the mode 1 (*c*, *f*): *a–c* — ×500; *d–g* — ×1800

them was determined in the regions of matrix, which do not contain primary intermetallics. The content of scandium and zirconium in different areas of welded joints is shown in Table 3.

Secondary intermetallics of the base metal contain about 0.10 % of Sc and 0.07–0.90 % of Zr. This means that in strengthening of stamped semi-finished products of 01570 alloy, not more than a half of the most expensive alloying element — scandium participated. And in a solid solution of the weld metal, scandium content increased and amounts to 0.11 % during welding at a speed of 16.8 mm/s (mode 2) and 0.12 % at a welding speed of 2.8 mm/s (mode 3). Zirconium content in a solid solution of welds amounts to about 0.1 %.

The mechanical properties of the weld metal of 01570 alloy produced at different welding speeds after artificial aging are shown in Table 4. When the welding speed grows from 2.8 to 16.8 mm/s, the strength and ductility of the weld metal increase. The ultimate strength of the weld metal increases from 375 to 385 MPa, the conditional yield strength grows from 230 to 240 MPa, and the relative elongation rises from 15 to 25 %.

RESEARCH RESULTS AND THEIR DISCUSSION

Let us consider the results of measuring hardness, obtained on the specimens produced on the modes 1 and 2 (see Table 2, welds of 3.5 mm width). From Figure 3, *a* it is seen that the hardness of all artificially aged welds is higher than the hardness of the base metal. Moreover, in welding at a speed of 2.8 mm/s, the hardness is higher than at a speed of 16.8 mm/s. Such an increase in hardness can be explained as follows. During the EBW process, nanosized secondary $A1_3$(Sc, Zr) intermetallics, contained in the base metal, are completely dissolved in a liquid metal of the weld pool. In addition, in the metal of the pool, a partial dissolution of relatively large primary intermetallics occurs. The longer the period of the weld pool existence, the larger part of refractory primary intermetallics succeeds in dissolving in a liquid metal. Therefore, at a low welding speed (2.8 mm/s), the content of scandium dissolved in a liquid metal is higher than at a high welding speed (16.8 mm/s). This is confirmed by an X-ray spectral analysis of a solid solution of the weld metal. In a solid solution of the weld metal, produced at speeds of 2.8 and 16.8 mm/s, scandium is contained in the quantities of 0.12 and 0.11 %, respectively. As was mentioned above, for the welds of 3.5 mm width, produced at welding speeds of both 2.8 as well as 16.8 mm/s, the rates of hardening are sufficient for all scandium dissolved in the weld metal, to be completely fixed in a solid solution during cooling. Further, at an artificial ageing of welded joints in the welds produced at a welding speed

Table 3. Content of scandium and zirconium in different areas of welded joints, wt.%

Place of determination	Sc	Zr
Primary intermetallics	21–22	17–18
Base metal in the areas that do not contain primary intermetallics	0.10	0.07–0.09
Solid solution of the weld metal:		
Mode 2	0.11	0.10
Mode 3	0.12	0.10

Table 4. Mechanical properties of welded joints of 01570 alloy, produced at different welding rates after artificial aging

Welding speed, mm/s (welding mode)	σ_t, MPa	σ_y, MPa	δ, %	ψ, %
2.8 (3)	374.2–378.0 375.4	229.5–231.1 230.3	14.7–15.4 15.1	38.3–41.5 40.1
6 (4)	375.6–376.2 375.8	226.1–232.4 229.2	14.6–15.2 14.9	26.4–28.3 27.2
12 (5)	377.2–384.1 382.6	232.2–232.3 232.3	17.7–18.3 18.1	20.9–21.8 21.2
16.8 (6)	379.8–386.4 384.2	236.6–239.7 238.5	19.1–26.0 23.5	41.5–42.0 41.8

of 2.8 mm/s, more strengthening secondary Al_3(Sc, Zr) intermetallics are precipitated than in the welds in welding at a speed of 16.8 mm/s, which causes their higher strengthening. A partial dissolution of primary Al_3(Sc, Zr) intermetallics, contained in the base metal is the reason that the hardness of both welds became higher than the hardness of the base metal.

Further, it was determined what is happening when the volume of the weld pool is increased. The hardness of the welds produced on the modes 1 and 2 (see Table 2, welds of 3.5 mm width) with the hardness of the welds, produced on the modes 3 and 6 (see Table 2, welds of 7.0 mm width) was compared. From Figure 3, it is seen that in this case, the hardness of the aged weld metal after welding at a speed of 16.8 mm/s remained at a level of 93 *HRB*, and at a speed of 2.8 mm/s, it decreased from 96 to 91–92 *HRB*. Such a decrease in hardness can only be explained by a reduction in the rate of hardening. As the width of the weld (i.e., the volume of the weld pool) increases, the time of the metal existing in the liquid state grows. I.e., in welding on the mode 3, in a liquid pool, dissolved no less, but most probably more both secondary as well as primary Al_3(Sc, Zr) intermetallics, as compared to welding on the mode 1.

In this case, the rate of cooling the weld metal and, accordingly, the rate of its hardening could only decreased. Thus, the rate of hardening was not sufficiently high for the full transition of scandium from the melt into an oversaturated solid solution and after aging, the density of precipitates of strengthening secondary Al_3(Sc, Zr) particles in the welds of 7.0 mm width (mode 3) appeared to be lower than in the welds of 3.5 mm width (mode 1). Thus, it can be concluded that the rate of hardening of $5\cdot10^2$ °C/c is minimal for the full transition of scandium dissolved in a liquid metal into an oversaturated solid solution. At least, this assertion should be fair at 0.11–0.12 % concentration of scandium in the melt, as it was in our studies.

The results of mechanical tests of the metal of the artificially aged welds are confirmed by the results obtained during the measurement of hardness. The higher the hardness of the weld metal, the higher its strength characteristics.

CONCLUSIONS

1. In the process of EBW of 01570 alloy in the weld pool, a dissolution of not only secondary but also of a part of primary Al_3(Sc, Zr) intermetallics occurs, contained in the base metal. The quantity of scandium dissolved in a liquid metal is determined by the time of the pool existence. Depending on the rate of hardening during cooling of the weld metal, scandium is fully or partially fixed in an oversaturated solid solution.

2. At 0.10–0.12 % concentration of scandium dissolved in the weld pool, its full transition to an oversaturated solid solution is provided by hardening at a rate of at least $5\cdot10^2$ °C/c.

3. In strengthening of stamped semi-finished products, about 50 % of scandium contained in 01570 alloy, is involved. The remaining scandium forms a composition of primary intermetallics of 1–15 μm size, nonuniformly distributed over the metal structure.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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