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EFFECT OF THERMAL CYCLES IN ELECTRON BEAM WELDING OF ALUMINIUM 1570 ALLOY ON MECHANICAL PROPERTIES OF WELDED JOINTS

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The effect of welding speed on strength of joints and size of the heat-affected-zone in electron beam welding of 1570 alloy was investigated. Thermal cycles in the tail part of the welding pool and spots in the metal surface in the near-weld zone were determined. According to the thermal cycles of the welding pool, the rate of hardening of the weld metal was calculated and its effect on mechanical properties of the joints before and after artificial aging was investigated. Decrease in the welding speed and, consequently, increase in the lifetime of the liquid phase leads to the growth of hardness of the weld metal after aging, which is probably associated with a more complete dissolution of primary scandium intermetallics and its transition to a supersaturated solid solution during cooling. Measuring the hardness of metal in the cross-section of the joints, according to the thermal cycles of the corresponding points, it was determined that the temperature of the beginning of the loss of strength of the metal in electron beam welding of 1570 alloy is in the range of 450–560 °C. It was found that artificial aging provides full strength welded joints with stamped semi-finished products, and explosion treatment is ineffective. It is possible to increase the strength of joints to the level of strength of hardened plates by 20 % applying plastic deformation and a subsequent artificial aging. 7 Ref., 3 Tables, 8 Figures.

Keywords: electron beam welding, aluminium alloy, welded joints, thermal cycles, mechanical properties, artificial aging

1570 alloy of the Al–Mg–Sc system is considered to be thermally unstrengthening, as far as during its production a strengthening heat treatment in the form of hardening and artificial aging is not used. However, during casting of semi-finished products of alloys, scandium is fixed in a supersaturated solid solution (i.e., hardening) and the alloy is strengthened during subsequent heating (i.e., aging) [1]. The high mechanical properties of the alloy are predetermined by the formation of strengthening particles of Al_3Sc phase, which is precipitated during heating and deformation from a supersaturated solid solution. One of the causes for the positive effect of scandium on the strength characteristics of alloys of the Al–Mg system is the stability of a nonrecrystallized structure formed as a result of pressure treatment, which is predetermined by the formation of secondary particles of Al_3Sc phase, precipitated during heating and deformation from a supersaturated solid solution. The second cause for strengthening is a direct strengthening action of the Al_3Sc phase particles [2].

Scandium refers to refractory elements and its introduction into low-melting aluminium alloys presents the known difficulties. To facilitate the assimilation of aluminium melt, the refractory element— scandium is introduced in the form of a master alloy Al – 2 % Sc. Moreover, the concentration of a solid solution of scandium in aluminium in the master alloy does not exceed 0.7–0.8 %. And most of scandium is in the form of primary $A1_3Sc$ intermetallics, which have a high thermal stability and are extremely slowly soluble in the aluminium melt. To accelerate this process, the melt is overheated [3]. Therefore, the dissolution of $A1_3Sc$ intermetallics is significantly affected by the temperature and time of a melt existence. In the production of semi-finished products of 1570 alloy, some part of scandium does not pass into a solid solution, but precipitated from the melt in the form of primary intermetallics, which contain Sc and Zr [1]. Thus, in the existing technologies of production, some part of the main strengthening and most expensive component of the alloy 1570 — scandium does not participate in its strengthening.

On the experimental Al–Mg–Sc alloys, at a scandium content of 0.4–1.0 %, it was found that at a hardening rate of 10^2 °C/s, scandium partially turns into a supersaturated solid solution, and partially crystallizes in the form of intermetallics. At a hardening rate of 10^5 °C/s much more scandium passes into a supersaturated solid solution, which facilitates 10^2 times increase in the density of precipitates of the strengthening Al_3Sc phase, formed during aging [4, 5]. With the use of such a highly concentrated heat source for welding as electron beam, it is possible to change the welding speed in a wide range, changing

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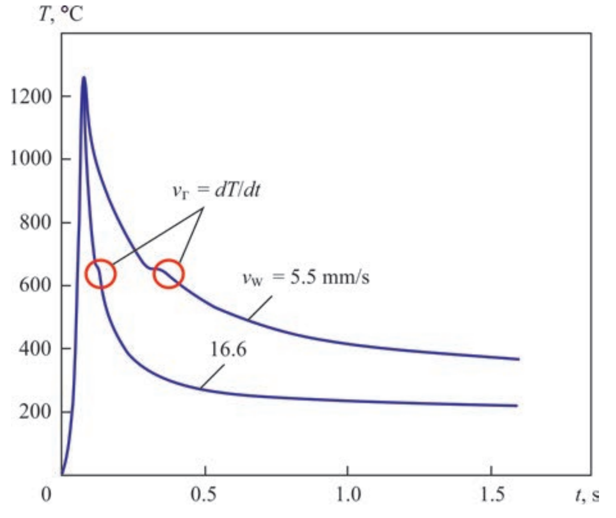

Figure 1. Measured experimental curves of cooling of welding pool metal in EBW of AMg6 alloy at different rates

the temperature of the welding pool, the lifetime of the liquid phase, and also the cooling rate of the weld metal immediately after solidification (i.e. hardening rate). Thus, we will probably be able to change the amount of fixed scandium in the solid solution, which will affect the strength of welded joints after further artificial aging.

The aim of the work is to experimentally determine the thermal cycles in the tail part of the welding pool and points on the metal surface in the heat-affected-zone (HAZ) during electron beam welding (EBW) of 1570 alloy. According to the thermal cycles of the welding pool, the hardening rate of the weld metal was calculated and its effect on the mechanical properties of joints was investigated before and after artificial aging. By measuring the hardness of the metal in the cross-section of the joints, the temperature of the beginning of softening of the alloy was found by the thermal cycles of the respective points. The effect of thermomechanical treatment on the strengthening of welded joints was also determined.

Experimental procedure. The thermal cycles of the welding pool and HAZ were determined in EBW of plates of aluminium AMg6 alloy (closest to 1570 alloy as to the chemical composition) of 15 mm thickness. Welding modes were selected in such a way as to provide a guaranteed penetration with the formation of a uniform weld reinforcement. When determining the thermal cycles of the welding pool in its tail part the brazed joint of chromel-alumel thermocouple was immersed and its readings were recorded with a recorder [6]. The temperature of the welding pool was recorded directly, and the instantaneous cooling rate was determined as the tangent of the angle of inclination of the temperature tangent to the function diagram at a point of interest to us. HAZ thermal cycles were determined from the readings of thermocouples that were caulked-in at a distance of 1, 3, 5, and 7 mm from the fusion line. In order to reduce the inertia of the measurements, the diameter of the wire for the manufacture of thermocouples was chosen as the minimum possible (0.1 mm). The readings of thermocouples were recorded with a N338 type recorder. The speed of the tape was 100 mm/s.

Experimental part. The curves of cooling the weld pool and the weld metal for different speeds of EBW are shown in Figure 1. From Figure 1 it is seen that after reaching its maximum, the temperature decreases according to exponential law. From the obtained curves, the rates of cooling the weld metal immediately after crystallization (quenching rate) were calculated. As the welding speed increases from 2.8 to 16.8 mm/s, the cooling rate grows from $5{\cdot}10^2$ to $1{\cdot}10^4$ °C/s. Investigations of the effect of hardening rate of the weld metal on the strength of welded joints were performed on stamped plates of 1570 alloy with a thickness of 30 mm. The chemical composition of the base metal and weld metal are given in Table 1.

The experiments were performed in an electron beam welding machine UL 209M with a power source ELA 60/60 with a voltage of 60 kV. During EBW, the beam current and the focusing current were selected from the condition of a guaranteed penetration and formation of a reverse weld bead. A circular scanning of a beam with a diameter of 1.5 mm and a frequency of 600 Hz was used. Welds had a width of about 3 mm with almost parallel boundaries of the penetration zone in the central and lower part.

Hardness measurements were used to evaluate the degree of loss of strength and changes in the properties of the weld metal and the HAZ Rockwell device with a load on a steel ball of 600 N according to the scale of B with a ball diameter of 1.0 mm was used. Thermal cycles of points on the surface of welding plates are shown in Figure 2, and the results of hardness measurements are presented in Figure 3. The figures show that for welding speeds of 2.8 and 16.8 mm/s, the width of HAZ does not exceed 3 mm. A short-term heating of 1570 alloy to 450 °C is not ac-

Table 1. Chemical composition (wt.%) of base metal and weld metal of stamped semi-finished product of 1570 alloy

Place of determination	Al	Mg	Mn	Sc	Zr	Si	Fe	Cu	Zn
Base metal	Base	6.45	0.32	0.16	0.025	0.041	0.07	0.014	0.02
Weld	»	6.35	0.31	0.16	0.025	0.040	0.06	0.015	0.02

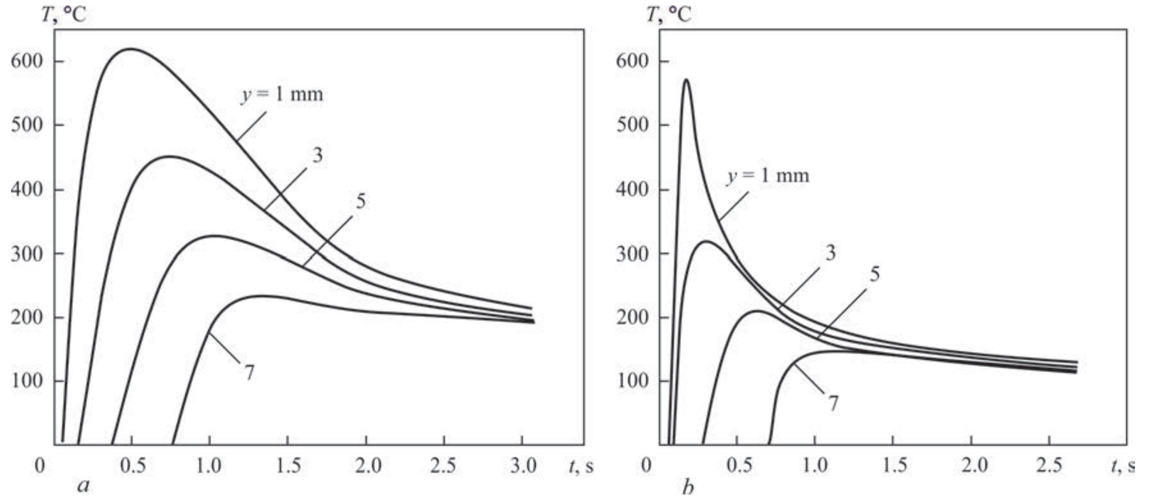

Figure 2. Thermal cycles of points on the surface of the plates of AMg6 alloy in EBW at a speed of: *a* —2.8 mm/s; *b* — 16.8 (*y* is the distance from the fusion line)

companied by a decrease in hardness. Short-term rises in temperature to 560 °C and higher lead to a decrease in hardness by 2–3 *HRB* units.

A part of the welded specimens was heat-treated for 1 h at a temperature of 350 °C. Hardness measurements in the cross-section of the joints and mechanical tensile tests of the specimens were performed (Table 2). Prior to heat treatment, the hardness of the weld metal was *HRB* 81–82 units. After artificial ageing, the hardness of the weld metal increased to a level exceeding the hardness of the base metal by *HRB* 1–2 units at a welding speed of 16.8 mm/s and by *HRB* 5–6 units at a welding speed of 2.8 mm/s. Therefore, with a decrease in welding speed, the hardness of the weld metal increased. Therefore, more reinforcing secondary Al_3Sc particles precipitated at low welding speeds after heat treatment. After welding, all the scandium contained in the weld metal should be either in a supersaturated solid solution, the decomposition of which causes strengthening of the alloy during aging, or in the form of primary intermetallics, which do not participate in strengthening of the alloy. The lower the welding speed, the lower the cooling rate, but the longer the time when the weld metal stays in a liquid state in the affected zone of the electron beam. Probably, an increase in the lifetime of the liquid phase led to the dissolution of more primary intermetallics and, accordingly, to the fixation of more scandium in a solid solution under cooling. Thus, the transition of scandium to a solid solution of the weld metal is affected by the welding speed more than the rate of further cooling and hardening of the metal. Thus, after electron beam remelting and a subsequent aging, the hardness of the weld metal is higher than the hard-

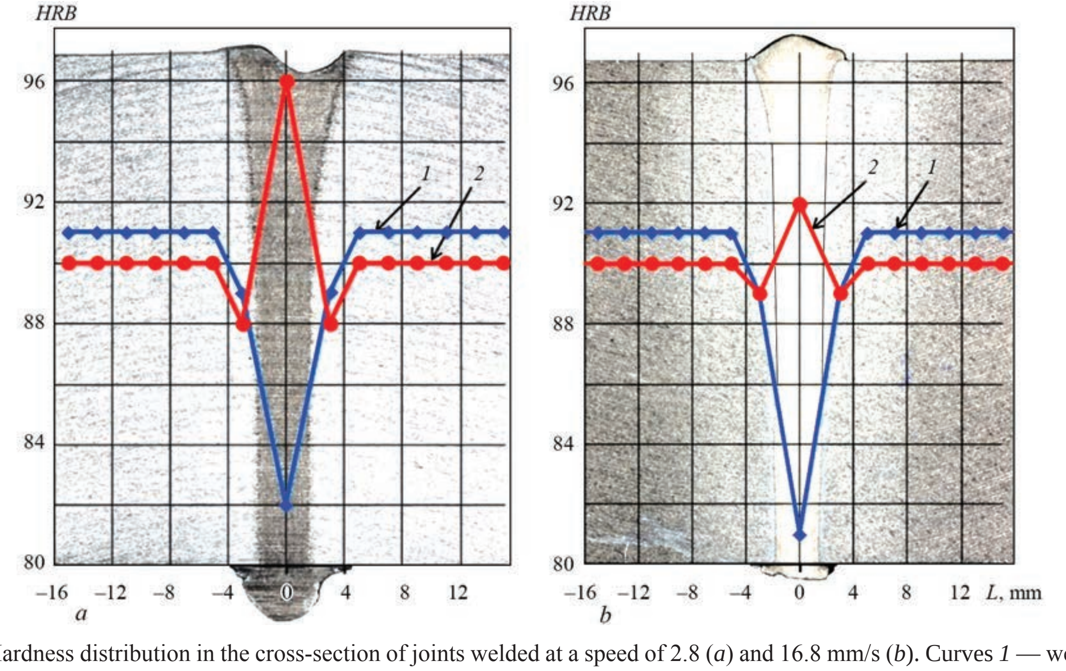

Figure 3. Hardness distribution in the cross-section of joints welded at a speed of 2.8 (*a*) and 16.8 mm/s (*b*). Curves *1* — welded joints without heat treatment; *2* — after artificial aging

Table 2. Ultimate tensile strength σ_t (MPa) of welded joints of stamped semi-finished product of 1570 alloy with a thickness of 30 mm without heat treatment and after artificial aging for different welding speeds

Welding speed, mm/s	Rate of hardening of weld metal, °C/s	σ_t of welded joint, MPa	σ_t of welded joint after artificial aging, MPa
2.8	>5·10^2	326–332 / 328	383–386 / 384 (*)
16.8	>1·10^4	329–332 / 331	385–387 / 386 (*)

Note. In the numerator the minimum and maximum values are shown, in the denominator the average value of the three measurements is shown. (*) is the fracture of 100 % of the specimens occurred on the base metal outside the HAZ.

ness of the original stamped semi-finished products of 1570 alloy. Probably, this occurs due to a more complete assimilation of scandium in the alloy.

From Table 2 it is seen that the strength of welded joints both before and after heat treatment depends little on the rate of hardening of the weld metal. The fracture of rupture specimens (Figure 4) occurs in the area with the lowest strength. Prior to artificial aging, such an area is a weld. After aging, all the specimens fractured on the base metal outside the HAZ, i.e. aging at 350 °C strengthens the weld metal to a level higher than the strength of the base metal. In cases where heat treatment of joints is provided after welding, the speed of EBW of 1570 alloy can be adjusted within wide ranges without a fear of decreasing their strength.

In some cases, it is possible to improve the strength properties of the weld and the heat-affected zone of aluminium alloys by explosion treatment of welded joints [7]. Studies of the effectiveness of such treatment as-applied to the joints of 1570 alloy were performed on stamped plates with a thickness of 60 mm, welded with an electron beam. Using explosives, the facial and then the reverse side of the joints were sequentially treated. The weld and adjacent areas of about 50 mm width were treated. Two treatment modes were used, which differed in the power of the explosive. When using a weak charge (mode 1), no noticeable deformation occured on the surface of the treated plates. A more powerful explosive (mode 2) deformed the treated plates up to 0.5 mm at the locations of the explosive. In Figure 5 the results of hardness measurements in the cross-section of welded joints are shown.

Explosion treatment increases the hardness of the weld metal at a distance of 10 mm from the surface of plates with *HRB* 82–83 to *HRB* 88–90. In the part of the weld, which is central as to the thickness of the joint, the hardness increased to *HRB* 86–88. The hardness of the base metal and HAZ after treatment increased slightly (by *HRB* 1–3 units). Some of the specimens after explosion treatment were artificially aged at 320 °C for 1 h. Heat treatment increased the hardness of the weld metal to the level of the base met-

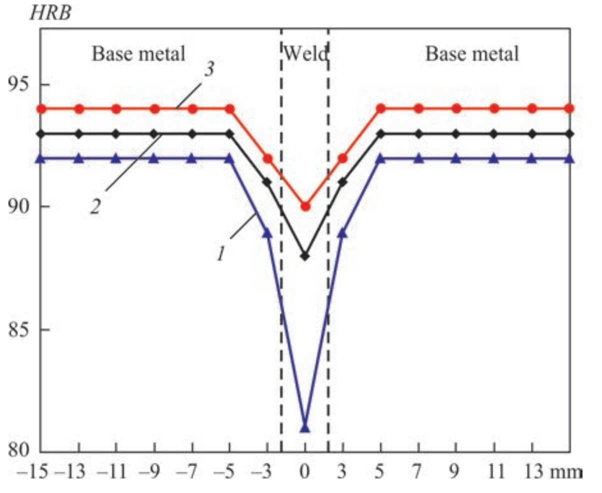

Figure 5. Distribution of hardness in the cross-section of welded joints of 1570 alloy at a distance of 10 mm from the surface of the plates (*1* — after welding; *2* — welding + explosion treatment on mode 1; *3* — welding + explosion treatment on mode 2)

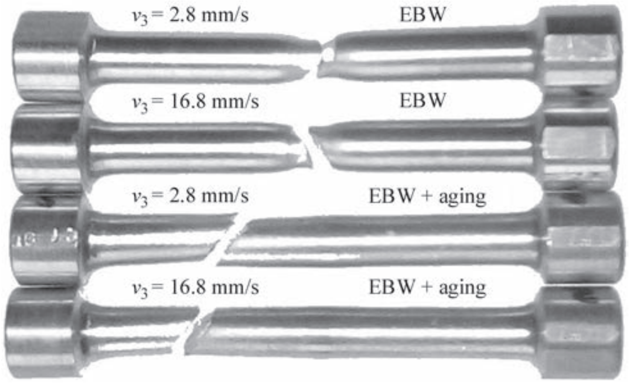

Figure 4. Nature of fracture of specimens after the test on rupture of joints of 1570 alloy without heat treatment and after artificial aging (welded joints are located in the center of specimens)

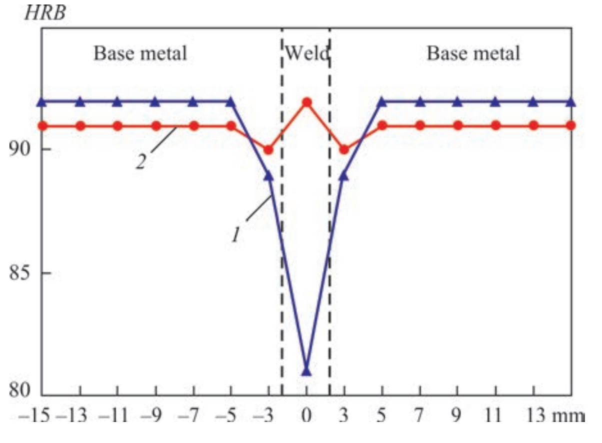

Figure 6. Hardness distribution in the cross-section of welded joints of 1570 alloy (*1* — after welding; *2* — welding + explosion treatment on mode 2 + artificial aging)

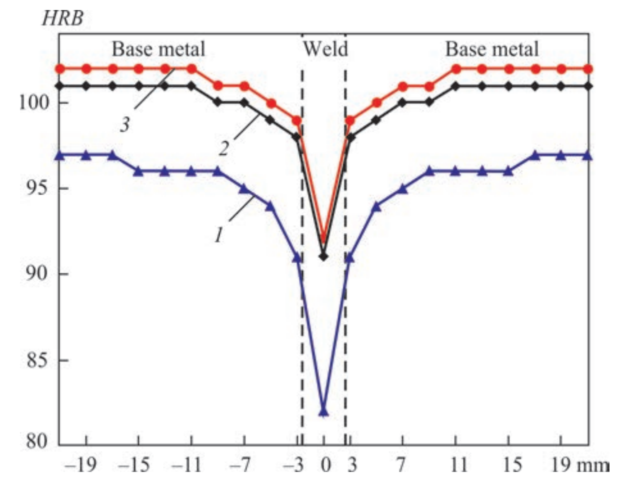

Figure 7. Hardness distribution in the cross-section of welded joints of hardened plates of 1570 alloy with a thickness of 26 mm (*1* — after welding; *2* —welding + hardening 20 %; *3* — welding + hardening 40 %)

al (Figure 6). Some decrease in hardness (by *HRB* 1–2 units) is observed only in HAZ, whose width does not exceed 3 mm.

The subsequent studies revealed that explosion treatment in the mode 1 did not affect the mechanical properties of the welded joints. As the explosive power increases (treatment on the mode 2), the ultimate tensile strength of the joints increases slightly (by 10–20 MPa). A subsequent heat treatment increases the ultimate tensile strength to the same level that is achieved also without an explosion treatment. Thus, the explosion treatment of welded joints of 1570 alloy is not only technologically complex, but inefficient and, therefore, is not rational.

Studies of the effect of plastic deformation on the mechanical properties of the joints of 1570 alloy were performed on hardened plates with a thickness of 26 mm. Cold plastic deformation was carried out by rolling. Before rolling, the reinforcement and the root of the weld were removed by mechanical treatment to the level of the base metal surface. The direction of rolling coincided with the direction of welding. The results of measuring hardness in the cross-section of welded joints are shown in Figure 7. Plastic deformation increases the hardness of the weld metal by *HRB* 81–82 to 91–93, and the base metal by *HRB* 94–95 to 101–103. The main increase in hardness occurs at the degree of plastic deformation from 0 to 30 %. A subsequent plastic deformation has no significant effect on the increase in hardness.

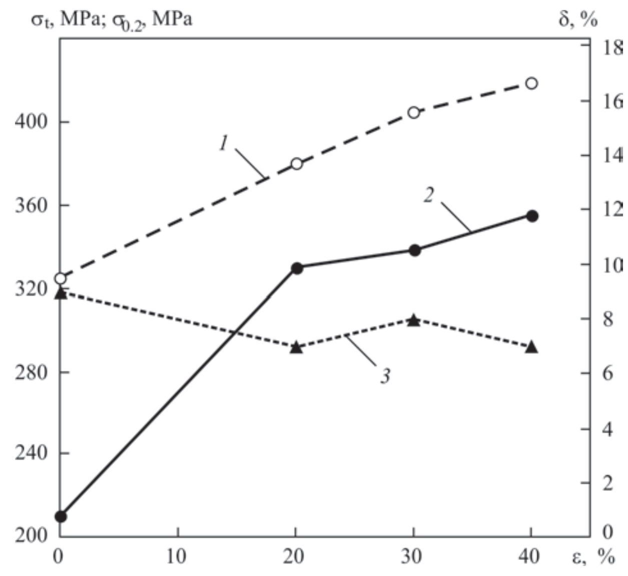

Figure 8. Mechanical properties of welded joints of hardened plates of 1570 alloy with a thickness of 26 mm depending on the degree of hardening (*1* — ultimate tensile strength σ_t, MPa; *2* — conditional yield strength $\sigma_{0.2}$, MPa; *3* — relative elongation δ, %)

Mechanical properties of the joints after rolling are shown in Figure 8. With an increase in the degree of deformation to 40 %, the ultimate tensile strength grows from 320 to 420 MPa, and the conditional yield strength grows from 210 to 350 MPa. It is important that plasticity of the joints does not change. At a deformation of 30 %, the strength of welded joints reaches the level of strength of hardened semi-finished products.

A part of the specimens after plastic deformation were aged at a temperature of 350 °C for 1 h. The test results of these specimens are given in Table 3. From Table 3 it is seen that the ultimate tensile strength of heat-treated specimens grows with an increase in the degree of plastic deformation. In all cases, artificial aging additionally increases the strength of the joints by 10–80 MPa.

Table 3. Ultimate tensile strength of base metal and welded joints σ_t (MPa) of hardened plates of 1570 alloy after hardening and artificial aging

Object of tests	Degree of plastic deformation, %			
	0	20	30	40
Base metal	402–415 410	–	–	–
Welded joint	320–332 325	362–384 376	402–411 408	412–424 419
Welded joint after artificial aging	392–402 396	401–405 404	415–419 417	424–426 425

Conclusions

It was found that artificial aging of welded joints produced by the EBW method, increases the hardness of the weld metal to the level, higher than the hardness level of the base metal of stamped semi-finished products. The greatest increase in hardness (5–6 units *HRB*) occurs at a low welding speed (2.8 mm/s) and, accordingly, at a low rate of hardening ($5\cdot10^2$ °C/s). Therefore, the rate of hardening does not play a crucial role in strengthening the weld metal during aging. On the other hand, a decrease in the welding speed increases the time when the metal stays in a liquid state in the zone of influence of the electron beam. Here, probably, not only dissolution of fine secondary $A1_3Sc$ particles, but also a more complete dissolution of large primary scandium intermetallics occurs. During cooling, scandium turns into a supersaturated solid solution, followed by precipitation of more reinforcing secondary $A1_3Sc$ particles during artificial aging.

After artificial aging, all specimens are fractured on the base metal outside the HAZ, i.e. in the cases when after welding heat treatment of joints is provided, the speed of EBW of 1570 alloy can be adjusted in a wide range without fear of reducing their strength.

The temperature of start of weakening the metal in the HAZ during EBW is in the range of 450–560 °C. The width of the HAZ in a wide range of welding speed change does not exceed 3 mm.

The effect of heat and explosion treatment, as well as plastic deformation on mechanical properties of 1570 alloy joints was studied. It was found that artificial aging makes welded joints equally strength with stamped semi-finished products, and explosion treatment has a low efficiency. It is possible to increase the strength of joints to the level of strength of hardened plates by 20 % applying plastic deformation and a subsequent artificial aging.

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MAY 2, 1969 Ocean liner «Queen Elizabeth 2» went on its first voyage Southampton — New York. For 35 years it was the flagship of the British Shipping Company «Cunard». The all-welded structure of the ship hull was divided into 13 waterproof transverse bulkheads. The outdoor deck, which is wood sheathed, was fastened on welded-on studs. As regards aluminium decks, because of application of thin material, the «springing» effect appeared when walking on the ship. This was largely overcome by cross-welding stiffeners on larger areas of the deck.

MAY 3, 1973 One day before the completion of the 108-storey building of Sears-Tower — a skyscraper in Chicago, USA, it becomes the tallest building in the world at that time (442.1 m). It is the hallmark of Chicago. Construction of such a building structure is a challenge for the construction and welding companies. About 76000 t of steels were used in construction. Lincoln Electric Company participated in the project as a construction partner. Its design contained 268 km of the main welds. Both electric arc and electroslag welding was used in construction of the building.

MAY 9, 1981 The sculpture-monument «Motherland», the largest statue in Ukraine (17th in the world), was opened on Victory Day. The figure of a woman holding up the shield and sword is faced with stainless steel sheets. The Statue height from the pedestal to the tip of the blade is 62 m, absolute height is 102 m, its weight is about 500 t. For the first time in the USSR, the sculpture of such a scale was manufactured at the Kiev Parizhskaya Kommuna Plant with technical support of PWI. More than 30 km of welds were made during its construction.