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EFFECT OF MODE OF ELECTRON BEAM WELDING, HEAT TREATMENT AND PLASTIC DEFORMATION ON STRENGTH OF JOINTS OF ALUMINIUM 1570 ALLOY

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The effect of the rate of hardening the weld metal during EBW process and the temperature of the subsequent heat treatment on the strength of welded joints of aluminium 1570 alloy was studied. The rate of «hardening» the weld metal was measured by submerging thermocouple into the molten metal of weld pool. At an increase in welding speed from 2.8 to 16.8 mm/s, the rate of «hardening» grows from $5\cdot10^2$ to $1\cdot10^4$ °C/s and the subsequent heat treatment of welded joints increases their strength to the level of strength of the base metal of stamped semi-finished products of 1570 alloy. It was established that during electron beam welding, the welding speed and, consequently, the rate of «hardening» do not affect the strength level of heat-treated joints. The optimal mode of heat treatment is artificial aging at a temperature of 350 °C and 1 h duration. It is possible to increase the strength of welded joints of 1570 alloy to the level of strength of rolled plates by 30 % applying a cold plastic deformation or by 20 % applying deformation with a subsequent artificial aging. 10 Ref., 3 Tables, 9 Figures.

Keywords: *electron beam welding, aluminium alloy, welded joints, welding speed, heat treatment, strength*

Scandium is the most effective hardener and modifier of aluminium alloys among other rare-earth metals. The main obstacle to the widespread use of scandium in metallurgy has always been its high cost. However, the development of new technologies for scandium extraction and production of Al–Sc master alloys made it possible to create industrial aluminium alloys of Al-Mg system alloyed with scandium [1].

The high-strength aluminium 1570 alloy is based on the well-known AMg6 alloy. The main difference between 1570 and AMg6 alloy is that it is additionally alloyed with the scandium element in the amount of 0.15−0.35 %. The introduction of 0.5 % Sc in the Al−6.5 % Mg alloy provides an increase in σ_t by 1.5 times and $\sigma_{0.2}$ twice, reaching 430 and 260 MPa, respectively [2]. The main increase in strength is provided with the introduction of small additives of scandium (0.2 %). The level of strength properties of 1570 alloy largely depends on the type of semi-finished product and can range from 370 to 450 MPa for σ_t, and from 240 to 340 MPa for $\sigma_{0.2}$. The higher the degree of deformation during pressure treatment and the lower the pressure treatment temperature, the higher the level of strength properties. Highly deformed cold-rolled sheets have the maximum strength, and massive hot-deformed semi-finished products manufactured with a small degree of deformation have the minimum strength [3]. One of the reasons for the positive effect of scandium on the strength characteristics of Al−Mg system alloys is the stability obtained as a result of pressure treatment of the nonrecrystallized structure, which is predetermined by the formation of secondary particles of Al_3Sc phase precipitated during heating and by the deformation from supersaturated solid solution. The second reason for hardening is the direct strengthening action of Al_3Sc phase particles [4]. Even small additions of scandium (0.15 %) cause a sharp increase in the temperatures of the beginning and end of recrystallization [5]. The strength of Al−6.5 % Mg–Sc alloys remains almost the same before recrystallization, and after its beginning it changes slightly.

Alloys of Al−Mg−Sc systems belong to the group of heat unhardened, because they are not subjected to heat treatment in the form of «hardening» and subsequent aging. However, the technological parameters for manufacture of semi-finished products of 1570 alloy are selected so as to provide the maximum transition of scandium to supersaturated solid solution (i.e. hardening) and regulated decomposition of this solution during subsequent heating (i.e. aging) [6]. The predominant mode of artificial aging was determined

*By hardening the authors understand superfast crystallization.

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in [7], where the effect of aging temperature on hardness and electrical resistance of Al–Mg–Sc alloys was studied. It was found that artificial aging at the temperatures of 150−200 °C is accompanied by a slight increase in hardness. In the case of increasing aging temperature to 250−350 °C, an effective hardening of alloys is observed. The maximum values of hardness are reached after artificial aging at 350 °C within 0.5−1.0 h. The decomposition of a solid solution abnormally supersaturated with scandium is characterized by high temperature, short incubation period and high stability of properties during heating to 300 °C. The data on the heat treatment modes that strengthen welded joints produced by EBW are not available in the literature.

During welding the weld metal is not subjected to pressure treatment and the only factor influencing the fixation of scandium in a supersaturated solid solution and, consequently, the ability of the molten metal to strengthening during artificial aging, is the rate of «hardening», i.e. in our case, the rate of cooling the weld pool metal immediately before crystallization. On the experimental Al−Mg−Sc alloys, maintaining scandium at 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 is partially solidified in the form of intermetallics. At a rate of «hardening» of 10^5 °C/s much more scandium passes in the supersaturated solid solution, which contributes to 10^2 times increase in the density of precipitations of the strengthening of Al_3Sc phase, formed during aging [8, 9]. Using such a highly concentrated heat source for welding as an electron beam, it is possible to change the welding speed in a wide range, changing the cooling rate of the weld pool metal, i.e. the rate of «hardening». Thus, we will probably be able to change the amount of scandium fixed in the solid solution, which will affect the strength of welded joints after further artificial aging.

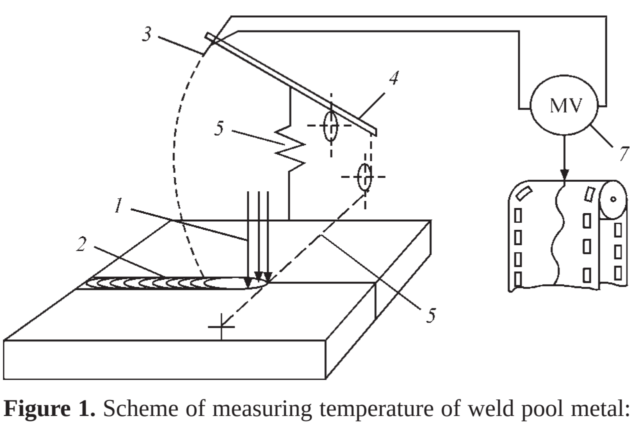

Figure 1. Scheme of measuring temperature of weld pool metal: *1* — electron beam; *2* — weld; *3* — thermocouple; *4* — balancing lever; *5* — holding wire; *6* — spring; *7* — self-recording device

The aim of this work is to determine the rate of «hardening» the weld metal at EBW of aluminium 1570 alloy, as well as the temperature of artificial aging and the degree of plastic deformation of welded joints, providing maximum increase in their strength.

It was of interest to determine the dependence of real cooling rate of the weld pool metal before crystallization (which for 1570 alloy will be the rate of the weld metal «hardening») on the welding speed. The experiments were performed in EBW of plates of aluminium AMg6 alloy (closest as to its chemical composition to 1570 alloy) of 15 mm thickness. The welding modes were selected in such a way as to provide a guaranteed penetration with the formation of a uniform weld reinforcement. A brazed joint of a chromel-alumel thermocouple was immersed in the tail part of the weld pool and its values were recorded with a self-recorder. The temperature of the weld pool was recorded directly, and the instantaneous cooling rate was determined as the tangent of the angle of inclination of the temperature function tangent to the diagram at the point of interest. In order to reduce the inertia of the measurements, the diameter of the wire for manufacture of thermocouples was chosen as the minimum possible (0.1 mm). The thermocouple readings were recorded with a N338 type recorder. The speed of the tape feed was 100 mm/s. The scheme of the experiment is shown in Figure 1.

The plates of AMg6 alloy were welded with an electron beam *1* to form a weld *2*. Thermocouple *3* was fixed at the end of the balancing lever *4*, located in such a way that in the lower position of the balancing lever the brazed joint of the thermocouple was immersed in a liquid metal pool on the weld axis. The balancing lever was in equilibrium under the action of the spring 6 on the one side and the holding steel wire *5* on the other. Thermocouple *3* was connected to the self-recorder *7*. Before conducting the experiment, thermocouple *3* was lifted by rotating the balancing lever *4* at an angle of about 45° with respect to the plane of the welded plates, stretching the spring *6* and fixing this position by securing the end of the holding wire *5*. In this position, the scheme of measuring the temperature of weld pool was ready for operation. During welding the holding wire was cut by the electron beam at the moment of crossing, and the balancing lever under the action of the spring lowered the brazed joint of the thermocouple in the tail of the weld pool. The lowering accuracy was adjusted by the position of holding wire relative to the brazed thermocouple, based on the actual dimensions of the weld pool, measured experimentally for different welding modes. Despite some primitiveness of the measurement scheme, it was possible not only to record the

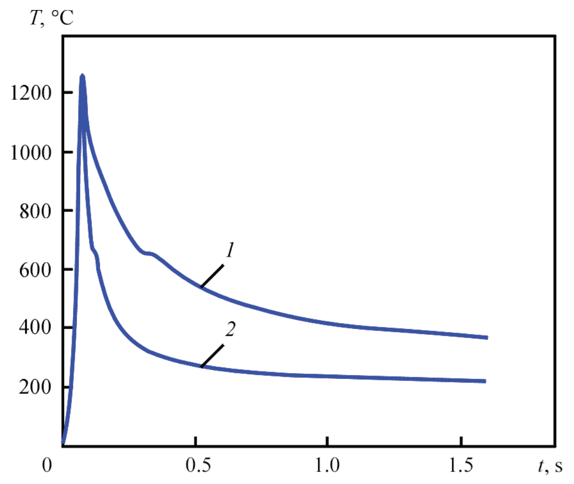

Figure 2. Examples of experimentally measured curves of cooling weld pool metal in EBW of AMg6 alloy at different speeds: *1* — 5.6; *2* — 16.8 mm/s

cooling curves of the weld metal, but also to record horizontal planes on them, which indicate the release of latent heat of crystallization. Metal cooling curves of the weld pool and weld for different EBW speeds are shown in Figure 2.

As is seen from Figure 2, at the beginning of the curve there is a sharp jump in temperature from 20 to 1200 °C. Then the temperature decreases exponentially. From the obtained curves, the cooling rates of the weld pool metal before crystallization were calculated (Figure 3). With an increase in the welding speed from 2.8 to 16.8 mm/s (from 10 to 60 m/h) the cooling rate increases from $5\cdot10^2$ to $1\cdot10^4$ °C/s. It should be taken into account that the error due to the inertia of the temperature measurement scheme could affect only the underestimation of the actual cooling rates. In this regard, we will consider these cooling rates to be minimal and in EBW of 1570 alloy will call them the rates of «hardening» the weld metal.

Investigations of the effect of the rate of «hardening» of the weld metal on the strength of welded joints were performed on stamped plates of 1570 alloy with a

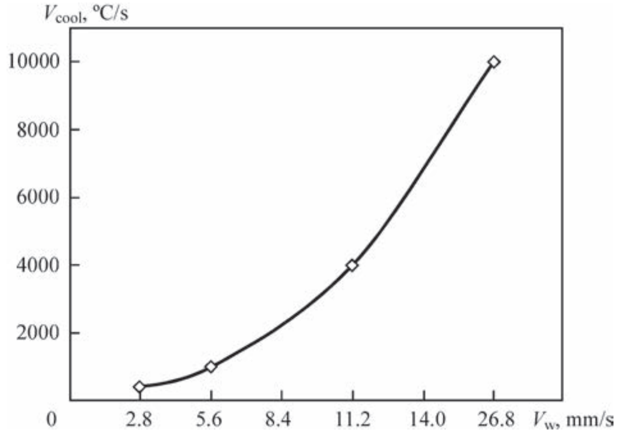

Figure 3. Dependence of cooling rate of weld pool metal before crystallization on welding speed in EBW of AMg6 alloy

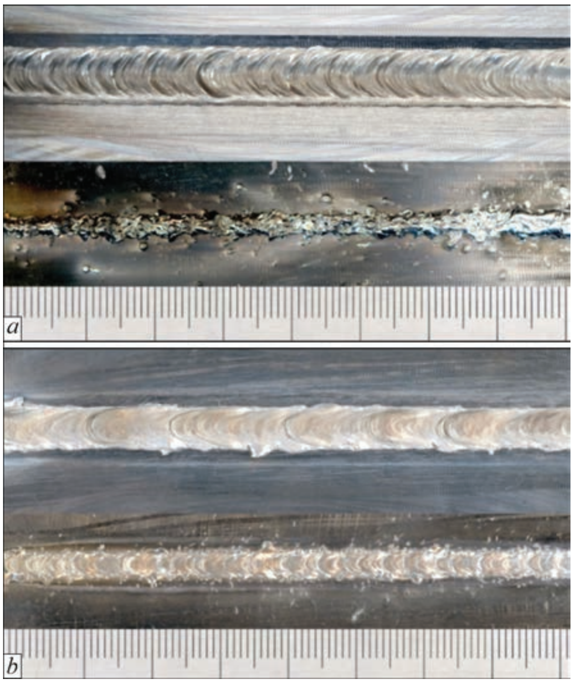

Figure 4. Facial side and root of the weld of specimens from stampings of 1570 alloy with a thickness of 30 mm, welded at the speeds of 2.8 (*a*) and 16.8 mm/s (*b*)

thickness of 30 mm. The experiments were performed in the electron beam welding machine UL-209M with the power source ELA 60/60 with a voltage of 60 kV. In EBW, the beam current and the focusing current were chosen from the condition of a guaranteed penetration and formation of the reverse weld bead. A circular scanning of a beam with a diameter of 1.5 mm and a frequency of 600 Hz was used. Two welding speeds were chosen: 2.8 and 16.8 mm/s, which correspond to the minimum and maximum speeds used in industry for EBW of high-strength aluminium alloys [10]. The appearance of welds is shown in Figure 4.

Cross-sections of welded joints are shown in Figure 5.

Welds have a width of about 3 mm with almost parallel boundaries of the penetration zone in the central and lower parts. From the side of the beam inlet, there is an increase in the width of the penetration zone to 4.5 mm for a welding speed of 16.8 and up to

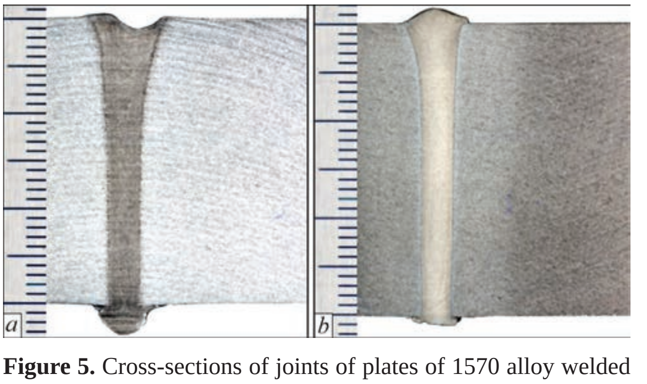

Figure 5. Cross-sections of joints of plates of 1570 alloy welded at a speed of 2.8 (*a*) and 16.8 mm/s (*b*)

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

Location of determination	Chemical composition, %								
	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	Same	6.35	0.31	0.16	0.025	0.040	0.06	0.015	0.02

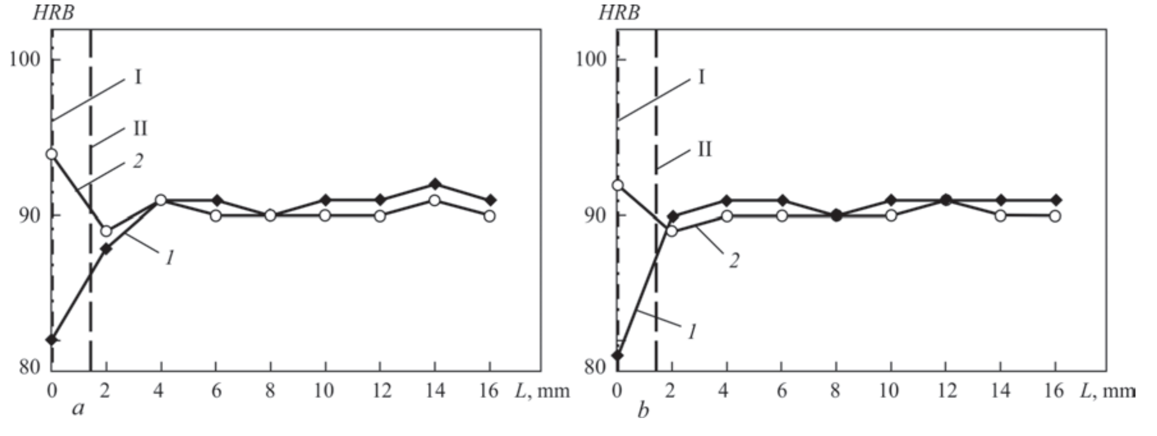

Figure 6. Distribution of hardness in the cross-section of joints welded at a speed of 2.8 (*a*) and 16.8 mm/s (*b*): curves *1* — welded joints without heat treatment; *2* — the same after artificial ageing at 350 °C; lines I — weld axis; II — fusion line

6 mm for a speed of 2.8 mm/s. At a welding speed of 16.8 mm/s, the weld has a uniform reinforcement on the front facial side and weld root and on the side of the beam inlet, the weld was formed with a decrease of about 1 mm in welding with 2.8 mm/s speed.

The chemical composition of the weld metal and the base metal of the stamped plates of 1570 alloy was determined using the equipment DFS-36 for spectral analysis. The results of the analysis are given in Table 1. As is seen from Table, the evaporation of alloying elements in EBW of 1570 alloy is insignificant. It is possible to note only a small decrease in the content of magnesium which losses make about 0.1 %.

The hardness measurements were used to assess the degree of decrease in strength and change in the properties of the weld metal and HAZ. The Rockwell device with a load on a steel ball of 600 N according to the scale B with a ball diameter of 1.0 mm was used. The measurement results are shown in Figure 6.

Table 2. Temporary resistance σ_t 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 at 350 °C, MPa
2.8	$>5\cdot10^2$	326–332 328	383–386(*) 384
16.8	$>1\cdot10^4$	329–332 331	385–387(*) 386

*In the numerator the minimum and maximum values and in the denominator the mean value of three dimensions are shown; (*) — fracture of 100 % of specimens occurred on the base metal outside the HAZ.

The hardness of the weld metal after welding is *HRB* 81–82. Artificial aging at a temperature of 350 °C increases the hardness of the weld metal to the *HRB* 92–94 and even makes it by 2–3 units higher than the hardness of the base metal. In the near-weld zone before and after heat treatment some decrease in hardness (by 1–3 units) is observed. The width of HAZ is about 3 mm for welding speed of 2.8 mm/s and, accordingly, decreases with increasing speed to 16.8 mm/s.

The strength of welded joints before and after artificial aging was determined by the tensile test of standard round specimens with a working part diameter of 9.0 mm. The test results are given in Table 2.

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 tensile specimens occurs in the area with the lowest strength. Prior to artificial aging, such an area is a weld. After aging, all specimens fractured along the base metal outside the HAZ, i.e. aging at 350 °C strengthens the weld metal to a level above the strength of the base metal. This is also evidenced by the measurements of the hardness of welded joints. This can be explained only by the fact that in EBW of 1570 alloy in the solid solution of the weld metal a larger amount of scandium is fixed than in the alloy itself during manufacture of stamped semi-finished products. Accordingly, during further heat treatment, the density of the precipitation of strengthening particles Al_3Sc in the weld will be higher than in the base

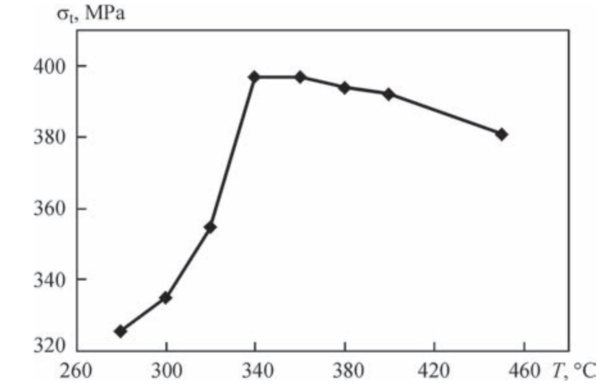

Figure 7. Dependence of temporary resistance of joints of plates of 1570 alloy of 26 mm thickness on temperature of artificial aging

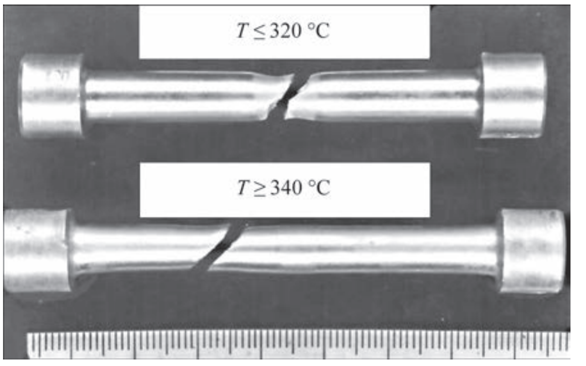

Figure 8. Nature of fractures of specimens after tensile tests of 1570 alloy artificially aged at different temperature

metal. Thus, in the range of welding speeds from 2.8 to 16.8 mm/s, the strength of the weld metal will be higher than the strength of the base metal. Thus, in cases where the heat treatment of the joints is provided after welding, the speed of EBW of 1570 alloy can be adjusted in a wide range without fear of reducing their strength.

Investigations of the effect of artificial aging temperature on the strength of welded joints of 1570 alloy were performed on rolled plates and stamped semi-finished products. The plates of 26 mm thickness were welded at a speed of 14 mm/s, stamping of 60 mm thickness is 1 mm/s. The welded joints of the plates were artificially aged at the temperatures from 280 to 450 °C for 1 h. The dependence of the strength of the joints of the plates of 1570 alloy on aging temperature is shown in Figure 7. The given data show that in the temperature range of 280−340 °C an effective strengthening of welded joints occurs. At the temperatures of 340−360 °C, the temporary resistance of the joints is maximum, and with a further increase in temperature, it begins to decrease. The decrease in strength at the aging temperature above 360 °C is probably predetermined by the beginning of recrystallization processes. All specimens subjected to aging at a temperature of 340 ° C and higher, fractured throughout the base metal outside the HAZ (see Figure 8). Thus, the optimal mode of heat treatment

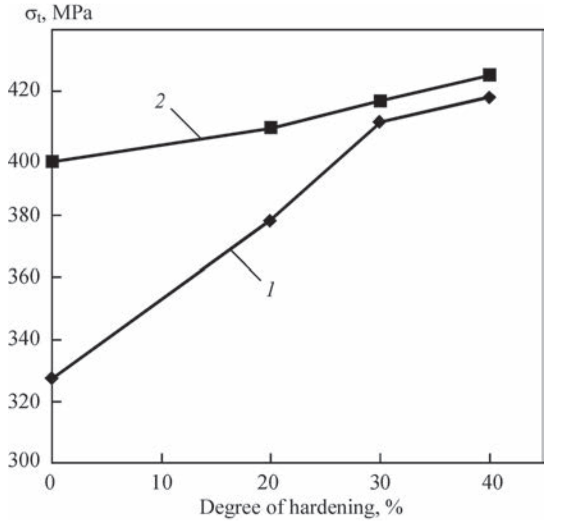

Figure 9. Temporary resistance of joints of plates of 1570 alloy with a thickness of 26 mm depending on degree of hardening: *1* — welding + hardening; *2* — welding + hardening + heat treatment

of welded joints of 1570 alloy produced by EBW is artificial aging at 350 ± 10 °C for 1 h.

Table 3 shows the results of tensile tests of specimens cut out from the base metal and welded joints of various semi-finished products of 1570 alloy without heat treatment and after artificial aging. The Table shows that the aging of welded joints at a temperature of 350 °C makes it possible to increase their strength by 50−70 MPa, and to reach the level of strength of

Table 3. Temporary resistance σ_t (MPa) of base metal and welded joints of various semi-finished products of 1570 alloy without heat treatment and after artificial aging

Type of semi-finished product	Base metal	Welded joint	Welded joint after artificial aging at 320 °C	Welded joint after artificial aging at 350 °C
Plate of 26 mm thickness	402–415 / 410	320–332(*) / 325	347–385(*) / 367	392–402(**) / 396
Stamping of 60 mm thickness	377–395 / 385	318–336(*) / 325	372–383(*) / 379	380–390(**) / 384

*In the numerator the minimum and maximum values and in the denominator the mean value of five dimensions are shown; (*) — fracture of specimens occurred on the weld metal; (**) — fracture of specimens occurred on the base metal outside the HAZ.

the base metal of the stamped semi-finished product of 1570 alloy before welding.

In order to achieve a uniform strength of welded joints of rolled plates of 1570 alloy with the base metal, they were subjected to cold plastic deformation by rolling. Before rolling the reinforcement and the root of the weld were removed to the level of plates surface. The direction of rolling coincided with the direction of welding. The strength of welded joints depending on the degree of plastic deformation is shown in Figure 9.

As the degree of deformation increases from 0 to 40 %, the strength of the joints increases from 320 to 420 MPa. At a plastic deformation of 30 %, the welded joints become equal in strength to the base metal of the rolled plates. Some of the specimens after rolling were heat-treated in a mode that provides the maximum increase in strength of the joints of 1570 alloy (artificial aging of 350 °C for 1 h). Heat treatment increases the strength of all specimens, and to achieve equal strength of the joints of rolled plates with the base metal it is enough to conduct plastic deformation by 20 %.

Conclusions

1. Measurements of the rate of «hardening» of the weld metal in EBW of the Al + 6 % Mg alloy and investigations of its effect on the ability of welded joints of 1570 alloy to strengthening during heat treatment were carried out. With increasing welding speed from 2.8 to 16.8 mm/s, the hardening rate increases from $5\cdot10^2$ to $1\cdot10^4$ °C/s. In this range of hardening rates, the artificial aging of welded joints of 1570 alloy increases the strength of the weld metal above the strength of the base stamping metal. This effect can be explained by the fact that in EBW more scandium passes into the solid solution of the weld metal than during the manufacture of semi-finished products of 1570 alloy. During artificial aging of welded joints, a larger amount of strengthening particles of Al_3Sc is precipitated from the solid solution in the weld metal than in the base metal. Thus, in cases where artificial aging of joints is used after welding, their strength does not depend on the speed of EBW.

2. Artificial aging of welded joints of 1570 alloy of 1 h duration provides the greatest increase in strength at an aging temperature of 350 °C. In this case, the welded joints produced by EBW become equal in strength to the base metal of the stamped semi-finished products.

3. It is possible to produce welded joints of 1570 alloy equal in strength with the rolled plates using cold plastic deformation by 30 % or deformation by 20 % with a subsequent artificial aging.

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