Investigation of mechanical properties of cold-rolled, annealed and welded semi-finished products from the test alloys of Al-Mg system, economically alloyed with scandium

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Abstract. The results of experimental investigation of mechanical properties of sheet metal from an experimental aluminum alloys Al–Mg system alloyed with scandium have been represented. It was established that the deformed and annealed semi-finished products of these alloys have higher strength properties. Testing of welded samples made from these semi-finished products showed high corrosion resistance and strength of welded joints.

1. Introduction
The problem of searching for new welded aluminum alloys having higher strength characteristics than existing industrial alloys of the Al-Mg system is most directly connected both with the creation of new, more sophisticated samples of new technology and with the solution of a number of national economic problems [1].

One of the most urgent problems of scientific and technical progress is the problem of increasing the weight perfection of missile and aircraft equipment, shipbuilding and the automotive industry. The main way to solve this problem is to increase the specific strength characteristics of structural materials by using new aluminum alloys with increased mechanical properties and corrosion resistance [2].

Studies in the field of creating alloys of the Al-Mg system doped with scandium and studying the properties of products made from them have been devoted many scientific publications, including foreign ones [3-12]. With the purpose of deeper studying the patterns of formation of mechanical and operational properties of products made of aluminum alloys economically alloyed with scandium, the employees of “RUSAL” together with scientists of the School of Non-Ferrous Metals and Materials Science of the Siberian Federal University have conducted a number of experimental studies in recent years with varying the chemical composition of alloys and regimes their processing, as well as produced batches of cast and deformed semi-finished products from them [13-16].

2. Experimental procedures
The ingots for rolling were obtained by casting alloys of the Al-Mg system with a scandium content of 0.1 to 0.24%. They were subjected to homogenization annealing according to the following regime: heating in furnace at a speed of 1.16 °C per minute to 350 °C; holding at this temperature for 11 hr;
reheating to temperature 425 °C with speed 1,25 °C per minute; holding at this temperature for 8 hr; air cooling.

Each ingot was rolled according to a deformation scheme adopted, including hot rolling a billet 40 mm thick heated to a temperature of 450 °C, up to a thickness of 10 mm, and then cold rolling of these strips to a thickness of 1 mm. Next, the strip was annealed at a temperature of 300 °C and holding time of 3 hr. As equipment for rolling, the DUO 330 mill was used (table 1).

Table 1. Technical characteristics of the sheet rolling mill DUO 330

| Parameter name       | Value |
|----------------------|-------|
| Electric motor power, kW | 90    |
| The mains supply voltage is three-phase, V | 380   |
| Current frequency, Hz | 50    |
| Width of barrel rolls, mm | 520   |
| Diameter of rolls, mm  | 330   |
| Maximum roll separation, mm | 70    |
| Rotational speed of rolls, rpm | 10    |
| Maximum rolling force, MN | 1.55  |
| The maximum rolling moment, MNm | 0.82  |

In the course of rolling, samples were taken for testing the mechanical properties and the temporary tensile strength \( R_m \), yield strength \( R_p \) and elongation \( A_{10} \) for each sample studied of alloys.

Mechanical properties after cold rolling at different degrees of deformation \( \varepsilon \) are given in table 2 (HR – after hot rolling, CR – after cold rolling at different degrees of deformation).

Table 2. Mechanical properties of samples from experimental alloys in a deformed state

| Alloy | Sc, % | HR | CR | HR | CR | HR | CR |
|-------|-------|----|----|----|----|----|----|
|       |       | \( R_m \), MPa | 40% | 60% | 80% | 40% | 60% | 80% | 40% | 60% | 80% |
| 1.    | 0.07  | 344 | 426 | 459 | 454 | 172 | 244 | 254 | 267 | 12.5 | 9.3 | 8.7 | 5.0 |
| 2.    | 0.09  | 350 | 438 | 470 | 494 | 225 | 237 | 256 | 274 | 12.2 | 8.2 | 7.4 | 4.8 |
| 3.    | 0.12  | 356 | 447 | 477 | 501 | 232 | 232 | 251 | 267 | 12.0 | 8.2 | 7.0 | 4.6 |
| 4.    | 0.13  | 373 | 460 | 478 | 505 | 235 | 232 | 257 | 372 | 11.7 | 8.3 | 7.0 | 4.2 |
| 5.    | 0.14  | 374 | 464 | 479 | 510 | 233 | 246 | 264 | 270 | 11.2 | 8.2 | 7.0 | 4.5 |
| 6.    | 0.14  | 360 | 465 | 480 | 513 | 245 | 295 | 314 | 278 | 10.6 | 8.1 | 7.0 | 4.4 |
| 7.    | 0.22  | 376 | 467 | 485 | 520 | 254 | 392 | 412 | 472 | 7.6  | 7.0 | 5.0 | 4.3 |
| 8.    | 0.24  | 380 | 476 | 490 | 554 | 250 | 395 | 414 | 488 | 7.0  | 6.3 | 4.6 | 4.2 |

The results of studies of the properties of the final products of rolling (annealed strips with a thickness of 1 mm) are given in table 3. Their analysis shows that the level of properties for experimental alloys containing scandium reaches elongation of values of about 21%. The yield strength of these alloys varies from 248 to 318 MPa.

Table 3. Results of studies of properties annealed strips of 1 mm thick

| Alloy number | Tensile strength \( R_m \), MPa | Yield strength \( R_p \), MPa | Elongation \( A_{10} \), % |
|--------------|-------------------------------|-----------------------------|-------------------------|
| 1.           | 407                           | 261                         | 21.2                    |
| 2.           | 412                           | 248                         | 14.8                    |
| 3.           | 425                           | 275                         | 14.3                    |
| 4.           | 435                           | 276                         | 12.8                    |
| 5.           | 462                           | 277                         | 12.1                    |
| 6.           | 463                           | 278                         | 12.0                    |
| 7.           | 474                           | 307                         | 10.3                    |
| 8.           | 487                           | 318                         | 9.2                     |
Data on the strength properties of semi-finished products from experimental alloy 3 containing 0.12% scandium, in comparison with the analog alloy 5083, which does not contain scandium, are given in table 4 and showed that the strength characteristics of economically alloyed alloy increased to a considerable extent, both in the deformed and annealed state.

Table 4. Strength properties of samples of rolled products from experimental alloys in a different state.

| Sample thickness, mm | Condition     | Strength properties, MPa | alloy 5083 | experimental alloy |
|----------------------|---------------|--------------------------|------------|-------------------|
|                      |               | $R_m$ | $R_p$ | $R_m$ | $R_p$ |
| 10                   | hot deformed  | 297  | 196  | 356  | 232  |
| 8                    | hot deformed  | 305  | 217  | 372  | 280  |
| 6                    | hot deformed  | 318  | 213  | 387  | 312  |
| 3                    | cold deformed | 394  | 373  | 453  | 429  |
| 3                    | annealed      | 277  | 139  | 390  | 277  |
| 1                    | cold deformed | 497  | 359  | 554  | 467  |
| 1                    | annealed      | 342  | 187  | 425  | 275  |

To study the properties of the welded seam, the resulting strips were welded along (method 1) and across (method 2) direction of deformation by means of argon-arc welding with filler wire from alloy 01570 (Figure 1), obtained by the method of combined casting and rolling-extruding with subsequent drawing. The mechanical properties of rods and wire are shown in table 5. Welding was performed using TIG-AC technology using a welding machine TIG200P.

Figure 1. View of welded samples.

Table 5. Mechanical properties of rods and wires from alloy 01570.

| Alloy   | Mechanical properties of semi-finished products | Wire Ø 3 mm |
|---------|-------------------------------------------------|-------------|
|         | Rod Ø 9 mm                                      | Wire condition | Tensile strength $R_m$, MPa | Elongation $A_{10}$, % |
| 01570   | Tensile strength $R_m$, MPa | Elongation $A_{10}$, % | Wire condition | Tensile strength $R_m$, MPa | Elongation $A_{10}$, % |
|         | 320                                            | 9.9          | Hardened        | 432                                      | 2.2          |
|         |                                                |              | Annealed        | 340                                      | 17.5         |
To assess the nature and degree of corrosion destruction of the investigated alloys, including in the weld zone, in accordance with State Standard 9.021-74 accelerated tests on the intergranular corrosion were performed (IGC). To do this, strips 3 mm thick were used, as well as samples welded from them with a welded joint along and across the direction of deformation. From the strips, tensile samples were prepared and placed in a solution containing sodium chloride solution and 0.3% hydrogen peroxide (58 g/l NaCl + 10 ml/l 33% solution H₂O₂). The temperature of the solution was 18-25°C, and the test duration is 24 hr. On all sides samples were washed with a solution, as shown in Figure 2. The samples were degreased with isopropyl alcohol before the IGC test and dried with filter paper. Then, etching was carried out for 2 minutes in a solution containing 50 ml of nitric acid (70%), 5 ml of hydrofluoric acid (48%) and 945 ml of water, at a solution temperature of 95±3°C; then the samples were washed in cold water and clarified in 25-30% nitric acid solution, then washed again and dried with filter paper. After the end of the test, the samples were washed under running water and dried in furnace at a temperature of 100±5°C within 5 minutes. After that, tensile tests were carried out and the mechanical properties of the samples in the weld zone.

Figure 2. Scheme of laying samples for tests on the IGC.

The results of investigations for some alloys are given in table 6. Tests for intergranular corrosion of samples after welding showed high corrosion resistance of welded joints, while the weld strength is 0.75-0.85 of the strength of the base metal.

Table 6. Mechanical properties of welded samples from experimental alloys

| Number of alloy/sample | Method for obtaining samples | Mechanical properties of samples after welding and annealing |
|------------------------|------------------------------|-----------------------------------------------------------|
|                        |                              | $R_m$, MPa | $R_p$, MPa | $A_{10}$, % |
| 2/1                    | 1                            | 362        | 246        | 6.0         |
| 2/2                    | 2                            | 353        | 293        | 3.3         |
| 3/1                    | 1                            | 361        | 250        | 6.0         |
| 3/2                    | 2                            | 334        | 245        | 2.6         |
| 5/1                    | 1                            | 351        | 242        | 5.7         |
3. Conclusion

Thus, the conducted studies made it possible to obtain data on the level and patterns of changes in mechanical properties from the total degree of deformation of rolled products from new alloys of the Al-Mg system doped with scandium in the range 0.10-0.24%, in a different state (hot deformed, cold deformed, annealed and welded). These data will be used in mastering the technology of casting and processing of these alloys in industrial conditions.

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