

Mechanical properties of RS-553 aluminum alloy at high strain rates

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The results of studies of dynamic properties of RS-553 powdered aluminum alloy samples obtained by additive technology (3D printing) by selective laser fusion are presented. The studies were performed using the traditional Kolsky method on a split Hopkinson rod at strain rates of $\sim 10^3 \text{ s}^{-1}$.

Keywords: Hopkinson split rod, RS-553 aluminum alloy, mechanical properties, additive technologies.

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Corrosion-resistant aluminum alloys of the Al–Mg–Sc system are currently being used or implemented in production of hull structures in various branches of mechanical engineering. These alloys have already proven themselves in aircraft construction and are being introduced into shipbuilding. Compared to aluminum-magnesium alloys, scandium-containing alloys provide a combination of higher physical, mechanical, and technological parameters [1].

However, the cost of intermediate products increases significantly even with a scandium content of 0.2–0.3 % in Al–Mg alloys, limiting their applicability in mass-production industries, such as automotive engineering or shipbuilding. In the context of wide application of aluminum alloys of the Al–Mg–Sc system, it appears promising to introduce additive technologies, which allow for a substantial reduction in material waste in the process of manufacture (if mechanical methods are used, up to 70 % of materials go to waste [2]). This would make it possible to reduce the cost of finished products to a level corresponding to (or even lower than) the cost of a similar product obtained using traditional technologies.

The RS-553 powdered aluminum scandium-containing high-strength non-heat-treatable alloy is one of the promising materials for aircraft engineering and shipbuilding. This alloy (TU 24.42.00-002-44669951-2019) is intended to be used in additive fabrication of products.

Aircraft and marine engineering products are often used in extreme ambient conditions with their structural elements subject to dynamic (impact) loads. Therefore, data on the mechanical dynamic characteristics of materials are needed to predict their behavior under impact excitations. The present study is focused on the determination of mechanical characteristics of alloy RS-553 at high strain rates ($\sim 10^3 \text{ s}^{-1}$).

Samples for dynamic and static tests were fabricated from the RS-553 powdered aluminum alloy of the Al–Mg–Sc system with a powder fraction of 20–45 μm . The scandium content of alloy RS-553 is $\sim 0.3 \text{ mass\%}$. Rods with a diameter of 11 mm for the production of samples were

obtained by 3D printing (selective laser melting in the vertical printing plane with subsequent annealing).

The sample for static tests was fabricated in accordance with GOST 1497–2023 (type III). A W+b LFM-50kN tensile testing machine was used to determine the static characteristics. The sample for dynamic tests was characterized in [3]. The dynamic characteristics of the RS-553 aluminum alloy were determined using an experimental setup implementing the Kolsky method with a split Hopkinson rod. The experimental setup was discussed in detail in [4].

The dynamic stress-strain (elongation) diagram obtained in accordance with the Hopkinson technique was plotted in the „true stress“ (σ_{tr})—„true (logarithmic) strain“ (ε_{tr}) coordinates. The true stress was calculated using the following formula:

$$\sigma_{tr} = \sigma(t)(1 + \varepsilon(t)), \quad (1)$$

while the true (logarithmic) strain was calculated as

$$\varepsilon_{tr} = \ln(1 + \varepsilon(t)), \quad (2)$$

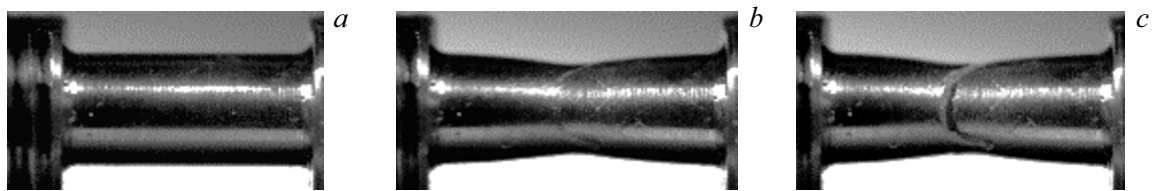
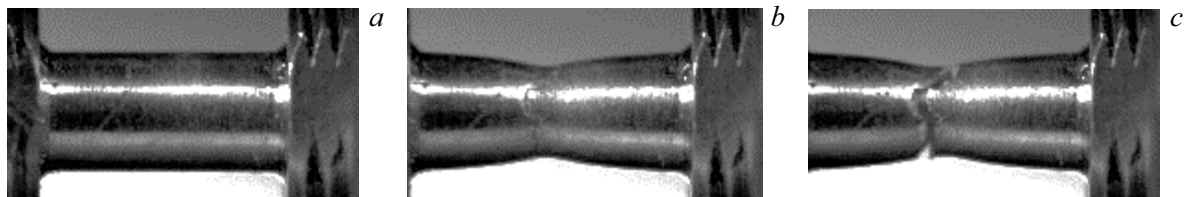
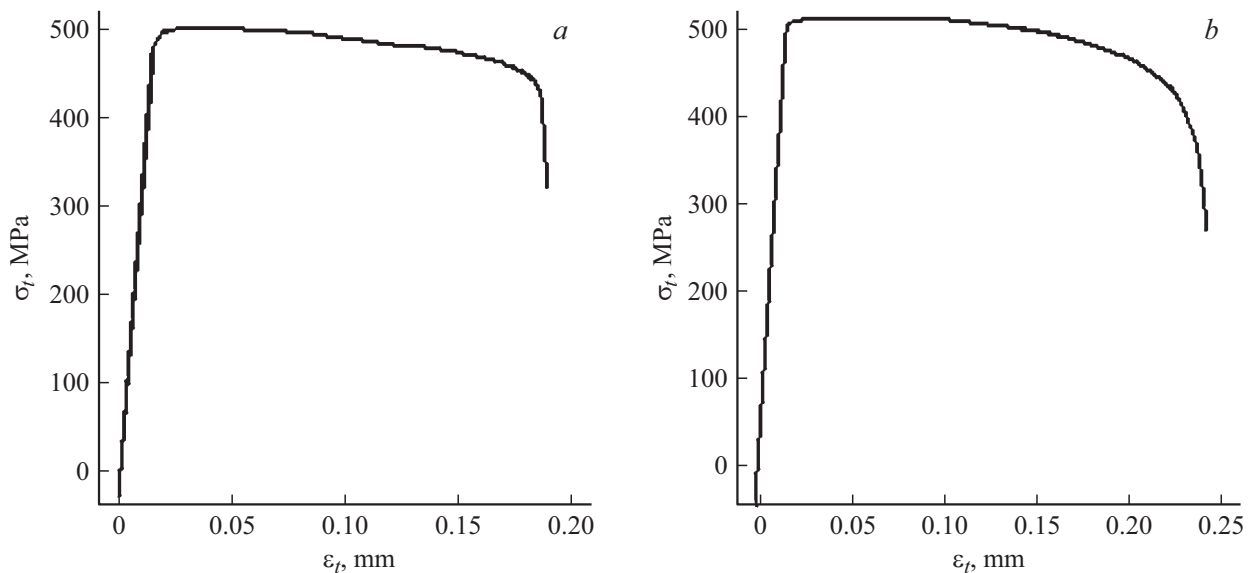
where $\sigma(t)$ is the average stress in the sample at time point t and $\varepsilon(t)$ is the average relative strain of the sample at the same time point t [5].

The results of dynamic and static tests of the RS-553 alloy are listed in the table. Statistical analysis of the results was carried out in accordance with [6]. Confidence intervals were calculated for a confidence level of 0.9 with a Student's coefficient of 2.9.

The images (Figs. 1, 2) obtained at strain rates $\dot{\varepsilon} = 1.4 \cdot 10^3$ and $1.9 \cdot 10^3 \text{ s}^{-1}$ reveal gradual necking with subsequent rupture of the samples at the thinnest point. At strain rate $\dot{\varepsilon} = 1.4 \cdot 10^3 \text{ s}^{-1}$, this rupture is of a shear nature. At strain rate $\dot{\varepsilon} = 1.9 \cdot 10^3 \text{ s}^{-1}$, the sample rupture is of a quasi-tearing nature (tearing with traces of plastic strain), which is probably associated either with a greater degree of material embrittlement at higher strain rates or with the presence of initial microdefects in the sample.

Results of static and dynamic tensile tests

Test type	Strain rate $\dot{\varepsilon}$, s^{-1}	True ultimate strength σ_B , MPa	True ultimate strength $\sigma_{0.2}$, MPa	Percentage elongation δ , %	Percentage reduction of area ψ , %
Dynamic (impact)	$(0.6-0.8) \cdot 10^3$	505 ± 20	505 ± 20	18 ± 4	35 ± 6
	$(0.9-1.4) \cdot 10^3$	510 ± 20	510 ± 20	20 ± 4	36 ± 4
	$(1.6-1.9) \cdot 10^3$	520 ± 15	520 ± 15	19 ± 5	35 ± 12
Static	1 mm/min	460 ± 5	425 ± 5	13 ± 5 (δ_5)	16 ± 4

Figure 1. Sample rupture at a strain rate of $1.4 \cdot 10^3 \text{ s}^{-1}$.Figure 2. Sample rupture at a strain rate of $1.9 \cdot 10^3 \text{ s}^{-1}$.Figure 3. Examples of load diagrams at $\dot{\varepsilon} = 1.4 \cdot 10^3$ (a) and $1.9 \cdot 10^3 \text{ s}^{-1}$ (b).

Examples of load diagrams are shown in Fig. 3. It can be seen that, in contrast to the results of static tests (see the table), the yield strength is virtually matching the ultimate strength.

Compared to the standard mechanical properties, the dynamic ultimate strength of the RS-553 alloy is 10–15 % higher than the static ultimate strength. At small strain magnitudes, the difference between the true dynamic

ultimate strength and the dynamic ultimate strength does not exceed 2%.

However, the dynamic percentage reduction of area is more than 2 times higher than the corresponding static values of this parameter that characterizes the material plasticity [7]. At the same time, it has been believed for quite a long time (since the publication of Davidenkov's work [8]) that an increase in strain rate leads to material embrittlement. However, it was concluded in [9–11] that the plastic characteristics of certain metallic materials (aluminum alloy of the Al–Mg–Li system, 35HS3MA and AK-25 steels, and titanium alloy VT23) get enhanced as the strain rate increases.

Since the samples differ in length, it is incorrect to compare them in terms of percentage elongation, which also characterizes plasticity.

It may be noted that the dynamic ultimate strength of aluminum alloy 1575-1 of the Al–Mg–Sc system is 450 MPa [3]; its scandium content is 0.12–0.2% [12], which is lower than that of the RS-553 alloy.

The results of experimental studies of the RS-553 aluminum alloy at strain rates $\dot{\varepsilon} = (0.6–1.9) \cdot 10^3 \text{ s}^{-1}$ suggest that it has high specific dynamic strength and plasticity levels, which make it a fine structural material for products manufactured using additive technologies that need to be relatively lightweight and compact and operate under extreme external loads.

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Conflict of interest

The authors declare that they have no conflict of interest.

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