Weldable aluminum armor. Status and prospects of production

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Abstract. In this paper, questions of production and prospects of development of armor materials on the basis of high-strength aluminum alloys of Al–Zn–Mg system are considered.

Alloys of the Al–Zn–Mg system are the most high-strength among the welded aluminum alloys and in this connection are widely used both as structural and as armor materials: 1901, 1903 (Russia), 7039, 7046 (USA).

All aluminum alloys, and especially alloys of the Al–Zn–Mg system, are prone to one of the most dangerous types of corrosion – corrosion cracking (CC) under the action of tensile stresses. The criterion for assessing the resistance to CC of alloys is the level of safe stresses (σ_cr) – the maximum tension at which there is no destruction of samples for a specified test period.

In armor aluminum structures, due to the absence of external stationary loads, the tension does not exceed 1 kg/mm^2. However, residual tensile stresses in welded structures made of plates 30–40 mm thick can reach values of more than 15 kg/mm^2. The used modes of heat treatment of welded armor structures allow reducing the level of these stresses to 7–8 kg/mm^2. The relatively low level of tensile stresses in such structures makes it possible to use as armor alloys more alloyed and, accordingly, more durable than structural alloys.

The total content of the main alloying elements (Zn + Mg) in the alloy 1901 is in the range of 7.8–9.2 wt. %, which provides the hardness of the plates in the state T1 (T1 – mode of heat treatment of the alloy to reach the maximum hardness) within 155–175 HV, the impact toughness a_n ≥ 0.45 kg m/mm^2. Heat treatment of welded structures made of plates 1901 allows to reduce residual stresses up to 7–8 kg/mm^2, i.e. to obtain properties (state T2, T3, HV = 140–155) optimal for this alloy both in armor and corrosion characteristics [1].

The level of safe stress σ_cr for welded joints of the plates of 1901 brand is 5–7 kg/mm^2 and the time to failure of samples in a high-rise direction at a tension of 15 kg/mm^2 is 20 days, which is insufficient to ensure high operational reliability even in conditions of slightly aggressive atmosphere.

The total content of Zn + Mg in the alloy 1903 is 6.8–7.9 %. Reduced by more than 1 % (compared with alloy 1901) level of alloying with zinc and magnesium allowed to significantly increase the ductility (1.5 times) and resistance to CC (2 times) of the alloy. At the same time, the strength properties decreased to 135–155 HV and, accordingly, the bullet resistance of the 1903 alloy plates is 10 % lower than that of the 1901 alloy plates.

It should be noted that the attempt to use alloy 7039 (USA) (analogue of alloy 1903) as welded armor was unsuccessful due to insufficient resistance of the alloy to corrosion cracking [2].
The development of aluminum armor with an increased level of armor properties in comparison with alloys 1901 and 1903 requires a simultaneous increase in both strength and plastic properties, and resistance to CC. A promising way to solve this problem is the use of layered aluminum [3].

Layered plates PAS-1 include surface (cladding) and an intermediate layer of technically pure aluminum of a thickness of 1–3 % of the plate thickness, the back layer of an alloy 1903 with a thickness of 7 ± 2 % and the main (front) layer of welded alloy 1931 [1] with thickness of 80–90 % of the thickness of the plate and providing hardness ≥ 170 HV. Figure 1 shows the layout of the layers in the PAS-1 plates.

![Figure 1. Layout of layers in PAS-1 plates.](image)

The outer layers of technically pure aluminum, having high corrosion properties, provide protection against CC in the zone of thermal influence of welds on the front and rear surfaces of parts made of PAS-1 plates; the intermediate layer of technically pure aluminum, which has high plasticity, provides a strong connection of layers and is a barrier to the passage of cracks formed in the main layer; the back layer of the alloy 1903 together with the cladding layer have sufficient plasticity to prevent the formation of back splits on the plate when it is fired at [4].

Further development of layered plates was the development of bulletproof armor brand PAS-1B. Figure 2 shows the arrangement of layers in the PAS-1B plates.

![Figure 2. Scheme of location of layers in the PAS-1B plates.](image)

Unlike PAS-1 plates in plates of the PAS-1B brand:

– the main (middle) layer is made of welded alloy 1931B brand [5] with hardness HV ≥ 180, which provided a weight reduction relative to the plates PAS-1 by 7 % while maintaining the level of bullet resistance. The increase in hardness of alloy 1931B relatively to 1931 alloy is achieved by increasing $\Sigma_{\text{av}} \text{Zn} + \text{Mg}$ from 9.6 to 10.0 %. However, the resistance to CC of 1931B alloy is 1.5 times higher than of alloy 1931 due to the introduction into the 1931B alloy of the regulated content of copper and increase of the ratio of Zn/Mg from 1.8 for alloy 1931 to 2.8 for the alloy 1931B;

– the back and front layers are made of alloy 1903A with increased ductility and corrosion resistance relative to the alloy 1903. Introduction to PAS-1B plate structure of the surface layer has enhanced its fatigue strength by 1.5 times and the survivability of plate, in particular, preventing formation of large surface layer splits when hit by a bullet cal. 12.7 mm in the vicinity of edge parts with a thickness of 40–50mm [6];
the outer and intermediate layers in the PAS-1B plates are made of alloy ACpl [1], providing both mechanical and electrochemical corrosion protection. The use of alloy 1903A and ACpl made it possible to increase the CC resistance of welded joints from PAS-1B plates by 1.4 times [7].

PAS-1B plates compared with homogeneous plates of 1901 alloy and welded steel armour brand st. 77 provides a weight advantage respectively 20 and 17 % with an equal level of armor protection.

As an anti-bullet and anti-shell armor, as an alternative to plates 1903, the production of layered plates of PAS-2B brand was mastered [4]. Figure 3 shows the layout of the layers in the plates PAS-2B.

![Figure 3. Layout of layers in the PAS-2B plate.](image)

Unlike PAS-1B plates in PAS-2B plates, the thickness of the back layer of 1903A alloy is increased to 15 ± 3 % of the plate thickness. To increase the plasticity of the back layer and, consequently, reduce the possibility of formation of rear splits during shell fire, a layer of 2 ± 1 % of ACpl alloy was introduced in the middle of the back layer. The middle (main) layer of a plate made of specially developed for these plates alloy grade 1931B2 [5], providing in T1 state (heat treated for maximum hardness) hardness 165–180 HV and having high ductility and resistance to CC compared to 1931B alloy used in the PAS-1B plates. PAS-2B plates at the equal level of armor resistance with plates of brand 1903, provide a weight gain of 10 %.

As an alternative to homogeneous plates of 1903 alloy and layered PAS-2B plates as an anti-bullet and anti-shell armor was mastered the production of plates of 1903A alloy [6].

Plates of 1903A brand due to reduced than in the 1903 alloy level of alloying of zinc and magnesium by 0.5 %, increased relationship of Zn/Mg from 2.1 to 3.1 and introduction of the regulated content of copper in quantity 0.1–0.25 % have CC resistance higher than that of the plates 1903 by more than 1.5 times. Plate of 1903A brand due to the additional alloying of manganese with equal strength to the 1903 alloy have ductility 20–30 % higher and therefore the armor properties of the plates of 1903A brand are somewhat higher than plates 1903:

- the cost of plates of 1903A brand is equal to the cost of the 1903 plates and is by 30–40 % lower than the cost of layered plates PAS-2B;
- open ends of welded corner joints in welded structures made of 1903A alloy do not require additional protection to increase the resistance to CC in contrast to the designs of plates PAS-2B, PAS-1, PAS-1(A) and 1903.

From perspective alloys of aluminum armor it is necessary to pay attention to the alloy with manganese content within 0.9–1.3 % [8], assuming simultaneous increase of armor and corrosion properties. In this case, this alloy can be a good alternative to both 1903A alloy and layered plates PAS-2B and become the basis for further development of new aluminum armor materials.

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