Mechanical properties and fatigue of extruded D16 alloy profiles of the Al-Cu-Mg system after ion irradiation

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Abstract. The effect of 20-keV Ar⁺ ion irradiation on the mechanical properties and fatigue resistance of 6 mm thick hot-extruded profiles made of a D16 alloy (Al–Cu–Mg system) has been studied after natural aging. Irradiation at fluences of 2×10¹⁵ cm⁻² and 1×10¹⁶ cm⁻² has been revealed to increase the number of cycles to failure significantly at low load amplitudes σ/σ_u = 0.3. The maximum increase in the number of cycles to destruction 2.4 times is observed at a smaller fluence of ions F = 2×10¹⁵ cm⁻².

1. Introduction
This work is to investigate the effect of Ar⁺ ion irradiation on the fatigue resistance of hot-extruded D16 alloy (Al–Cu–Mg system) profiles in the as-delivered state (after quenching and natural aging).

The D16 alloy, the classic duralumin, is characterized by high strength and high ductility. It is widely used as a structural material in various fields of modern technology, including aircraft construction [1, 2]. The changes in the microstructure, phase composition and mechanical properties of cold-worked VD1 and D16 alloy sheets (Al–Cu–Mg system) 2–3 mm thick after Ar⁺ ion irradiation were previously presented in [3]. The ion-beam treatment regimes were selected to ensure the softening of these alloys to the required level of properties, which allows further cold-rolling of the alloys. Based on these results, we patented the technology of intermediate radiation annealing of commercial aluminum alloys during their cold rolling, which provides a 2–3 times reduction of labor and energy consumption of the processes as compared to heat treatment [3].

Therefore, it is of interest to search for opportunities to enhance the mechanical properties and resource characteristics of the D16 alloy using ion-beam irradiation as a finishing treatment.

2. Experimental part
Hot-extruded PR-100-23 profiles (6 mm thick) [4] made of the D16 alloy after quenching and natural ageing were provided by Kamensk-Ural’skii Metallurgical Works. Standard samples for mechanical and fatigue tests were previously made from these profiles.

The samples were irradiated using an ILM-1 ion beam implanter equipped with a PULSAR-1M ion source based on a glow discharge with a hollow cold cathode [5]. A ribbon ion beam 100×20 mm² was cut from the cylindrical ion beam using a collimator. To decrease the heating temperature, the samples were irradiated from both sides while moving them under the ion beam at a speed of 2.5 cm/s. The
temperature of the samples during irradiation was controlled with a chromel–alumel thermocouple welded to a similar test sample and a computerized digital signal measurement system based on ADAM-4000 modules. The maximum temperature to which the samples were heated during irradiation was below 30–40°C. We used the following ion beam parameters: ion energy \( E = 20 \text{ keV} \), ion current density \( j = 200 \mu\text{A/cm}^2 \), and fluences \( F_1 = 2 \cdot 10^{15} \text{ cm}^{-2} \) (irradiation time was 1.6 s) and \( F_2 = 1 \cdot 10^{16} \text{ cm}^{-2} \) (irradiation time was 8 s).

Samples were tested on an INSTRON-8801 universal servohydraulic tester equipped with a computer and a FastTrack controller. All operations during the experiment were performed using hardware-software tools. Sinusoidal cycle fatigue tests were performed at a loading frequency of 3 Hz to determine the Weller fatigue curve. The asymmetry coefficient of the cycle was \(-1\).

3. Details of exposure, measurements, and results

As a result of tests for uniaxial tension of the initial and irradiated samples of D16 alloy, it was found that after quenching and natural aging, D16 alloy has the following mechanical properties: \( \sigma_u = 557 \text{ MPa} \), \( \sigma_{0.2} = 441 \text{ MPa} \), \( \delta = 9.7 \% \). The mechanical properties after ion irradiation at fluence \( F = 2 \cdot 10^{15} \text{ cm}^{-2} \) remain almost the same. Irradiation at a higher fluence \( F = 1 \cdot 10^{16} \text{ cm}^{-2} \) increases the relative elongation to \( \delta = 12.3 \% \), without changing the strength properties (changes within the measurement error): \( \sigma_u = 545 \text{ MPa} \) and \( \sigma_{0.2} = 435 \text{ MPa} \).

Figure 1 shows the Weller curves built based on the results of the tests of the initial and irradiated D16 alloy samples. The number of cycles to destruction at \( \sigma/\sigma_u = 0.3 \) is seen to increase significantly after irradiation under the used conditions. The number of cycles to destruction for the initial sample is 633 757 cycles, whereas it is 1 523 825 cycles after irradiation at a fluence of \( 2 \cdot 10^{15} \text{ cm}^{-2} \) and 1 000 000 cycles at a fluence of \( 1 \cdot 10^{16} \text{ cm}^{-2} \).

![Figure 1](image.png)

**Figure 1.** Number of cycles \( \lg(N) \) as a function of maximum cyclic stress \( \sigma \) for the D16 alloy samples before and after Ar+ ion irradiation (\( E = 20 \text{ keV} \)).
This phenomenon may be due to the fact that small elastic deformations occur under conditions of multi-cycle fatigue [6, 7]. Moreover, the surface and the volume of the irradiated sample are subjected to instantaneous ion-beam radiation annealing [3]. As a result, both the surface and the volume become almost free of deformation defects. Therefore, the failure starts from the sample surface much later, since the processes involving damage accumulation and cracking develop much slower. Low-cycle fatigue causes elastoplastic deformations and defects accumulate across the entire sample cross section [6, 7].

4. Conclusions
This research showed that short-term (8 s) Ar⁺ ion irradiation of the D16 alloy at an ion energy of 20 keV and fluence $F = 1 \times 10^{16}$ cm⁻² increased the plasticity of the alloy and retained its strength characteristics. The irradiation at fluences of $2 \times 10^{15}$ cm⁻² and $1 \times 10^{16}$ cm⁻² was revealed to increase the number of cycles to failure significantly at low load amplitudes $\sigma/\sigma_u = 0.3$. The maximum 2.4-time increase in the number of cycles to destruction was observed at a smaller fluence of ions $F = 2 \times 10^{15}$ cm⁻².

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