Research on the impact of aluminium alloys forming technology on the resistance to fatigue

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Abstract. The research is devoted to the evaluation of the impact of aluminium alloys processing by pressure in creep on the resistance to fatigue. Using the developed accelerated, non-destructive method, the kinetics of the total deformations response (longitudinal and transverse components) during deformation of the sample with increasing loading is considered. In the frames of this method, the limiting stresses are determined, a conservative estimate of the endurance limit for V95 and V-1461 aluminium alloys (analog 7475) (Al-Zn-Mg-Cu) and (analog 2099) (Al-Cu-Li-Zn), respectively, is obtained. Thick plates (40 mm) are molded on the UFP-1M equipment in creep, and surface control is carried out. More than 80% of the plate’s area is molded with a deviation of less than 1 mm from the nominal size. The microstructure of V-1461 alloy is studied before and after forming, and fatigue tests are performed on samples made of molded panels. Analysis of the research results showed that for the V95 and V-1461 alloys, the selected characteristics of the technological process of forming and heat treatment do not impair the fatigue properties of the studied alloys.

1. Introduction

Despite the fact that the use of composite materials in aviation technology has increased [1], the possibilities of high-strength aluminium alloys are not exhausted. It is worth paying attention to aluminium alloys on the basis of the Al-Zn-Mg-Cu system, which traditionally is used as basic material to manufacture the airframe’s structural elements. In recent years, prospects for the use of high-strength V-1461 aluminium-lithium alloy (similar to 2099) in the construction of new aircraft instead of V95 have been widely studied [2]. The V-1461 mechanical properties exceed those of V95: the density is 25% lower, elasticity is 9% higher, the specific strength is 11% higher, the yield strength is 14% higher, heat resistance and corrosion resistance are 1.5÷2 times higher [3].

When solving the problems of aviation technology associated with reducing the aircraft weight, we can offer to:

- apply in the construction of parts new aluminium alloys of reduced density, for example, V-1461, alloyed with lithium, each per cent of which reduces the density by 3% and increases elasticity by 6% [1, 3, 4];
- use of creep processes close to superplasticity in metal processing, which will ensure the preservation of the fatigue strength, reduce the construction’s weight [5] as well as time and cost of the part’s mechanical processing.

The considered technological process of forming in creep and close to superplasticity state was implemented on the UFP-1M equipment [6, 7], which ensures the production of the panel in a given range of maximum deviations for size, shape tolerances and surface locations.

Since the problem of the aviation materials strength under cyclic loading is important in aircraft construction, the evaluation of the impact of the forming technology on the resistance to fatigue for the V95 and V-1461 alloys is relevant.

Testing material samples using the accelerated method [8, 9, 10] allows one to reduce the costs and duration of the fatigue testing. However, according to, for example, the IAC aviation rules, the suitability and durability of materials used to manufacture the aircraft’s parts, the breakdown of which may affect safety, must be accompanied by experimental verification.

The aim of the study is to evaluate the effect of metal forming in creep on resistance to fatigue.

2. Samples, equipment, method and technology

2.1 Test samples

To reduce the number of fatigue tests, the deformation properties of the alloy samples were studied. These studies made it possible to estimate the ultimate stress of the material fatigue using the accumulation diagram of irreversible deformations. The samples of type IV were used due to GOST 25.502-79. For fatigue tests, samples of type VII were used due to GOST 25.502-79, \( K_t = 2.6 \), made of V-1461T1 and V95 plates. \( K_t \) is the theoretical coefficient of normal stress concentration.

2.2 Equipment

To determine the sample’s deformation properties and cyclic durability, the Instron 8801 universal test system was used in the comparative testing of samples from the material subjected to forming. Soft loading was carried out when testing the samples. To measure the increment of the total strain tensor, standard extensometers were used: No. 2620-601 "Dynamic Extensometer", "Transverse / Diametral Extensometer" No. W-E-404-F.

For carrying out forming of plates made from the V-1461T1 and V95 aluminium alloys, universal technological equipment was used — the UFP-1M equipment for panels forming in creep [11]. For heat treatment of the plates after forming, the VZA-6 air-hardening unit was used, for ageing - the PAP-27 aerodynamic heating furnace.

The compliance of the formed plates surface from the given theoretical model was monitored using a contactless coordinate measuring system based on the MV 224 laser radar. The measurement error for sizes up to 5000 mm does not exceed 22.5 microns. The microstructure was examined on a Carl Zeiss Axio Observer A1m microscope.

2.3 Method

2.3.1 Determination of the material’s deformation properties under cyclic loading. When studying new materials usually the ultimate stress (GOST 23.207-78) is determined in a destructive way. In the frames of this research, the method used in [9, 10, 12] was applied to determine the limit stresses, where they can be determined using an accumulation diagram for irreversible deformations or from the temperature of the material dissipative heating.

Figure 1, in coordinates: \( \varepsilon_{\text{max}}, \varepsilon_{\text{min}}, \varepsilon_{\text{max}}, \varepsilon_{\text{min}} \) vs. \( \sigma_{\text{max}}, \sigma_{\text{min}} \), experimental diagrams of the irreversible deformations accumulation for smooth samples made of V-1461 alloy according to the program with a stepwise increased loading are presented: with tensile cycles (2), compressive (3) and symmetric (1) stress cycles. The index “x” means the direction along the sample (the loading direction), “y” is the transverse direction.
Figure 1. Irreversible strains accumulation for smooth samples with a stepwise increased loading.

The diagram of the irreversible deformations accumulation presented in Figure 1 shows that the V-1461 deformation during the zero-to-tension stress cycle, both in the area of tensile stresses (2) and in the area of compressive stresses (3), occurs symmetrically. This characterizes the isotropy of the V-1461 properties, which does not depend on the sign of stresses in periodic loading.

When the amplitude exceeds 175 MPa in the area of both tensile and compressive stresses in the sample, dissipative processes are activated, as evidenced by the irreversible deformations accumulation.

The fatigue limit for the V-1461 and V95 alloys correspond to 350 MPa and 250 MPa, respectively [13].

The stress levels at which the V95 alloy fatigue tests were carried out are greater than the limiting stress for this material, determined by an accelerated method on smooth samples. Using the material endurance limit (the sample without a stress concentrator), which was 250 MPa, the calculated sample endurance limit with an opening was determined by formulas (1) and (2) [14]:

\[ K_{ij} = q(K_r - 1) + 1, \]
\[ \sigma_{ij} = \frac{\sigma_f}{K_{ij}}, \]

where \( K_{ij} \) is the effective coefficient of normal stress concentration, obtained by the calculation method, determined on the basis of the \( q \) average value. It is the coefficient of the material sensitivity to stress concentration. For the aluminium alloy \( q=0.85 \) with the hole radius \( r=3 \) mm [14]. \( \sigma_f \) and \( \sigma_{ij} \) are the limits of the sample’s limited endurance under axial loading without a concentrator and with a stress concentrator, respectively.

Then for the V95 alloy:

\[ K_{ij} = q(K_r - 1) + 1 = 0.85 (2.6 - 1) + 1 = 2.36, \quad \sigma_{ij} = \frac{\sigma_f}{K_{ij}} = \frac{250}{2.36} = 106 \) MPa.
First and second stress levels \((\sigma_{\text{net}}^{\text{max}1} \text{ and } \sigma_{\text{net}}^{\text{max}2})\) for the B95 alloy with a stress concentrator, for which fatigue tests were carried out, higher than the endurance limit \((\sigma_{ef} = 106 \text{ MPa})\), obtained by accelerated evaluation.

For the V-1461 alloy, the assigned stress levels during testing were the same, which made it possible to evaluate the resistance to the materials fatigue. At the same time, the difference between the test stress and the limit stress \((\sigma_{ef} = 148 \text{ MPa})\) was smaller. This made it possible to obtain a comparative evaluation of the materials properties at bases up to \(10^6\) cycles.

2.3.2 **Technological process of forming plates of complex geometry.** The technological process of plates forming (1800x800x40 mm) in creep at the UFP-1M equipment is described in [11]. As follows from [11, 13], the optimum temperature for forming a thick panel from V-1461 is \(T = 470°C\), and for V95 \(T = 420°C\). For the V-1461 alloy, it is the temperature of rolled plates [15].

Heat treatment of formed plates included quenching and ageing [13].

2.3.3 **Statistical processing of results.** To build the curves of the durability and endurance limits distribution, estimates of average values and standard deviations, the test results are subjected to statistical processing.

3. **Main results**

3.1. **Fatigue characteristics of the V-1461 and V95 plates after forming and heat treatment**

After forming, samples were made of plates for fatigue tests at Instron 8801. Samples were tested at two loading levels at maximum cycle stress \(\sigma_{\text{net}}^{\text{max}1} = 157 \text{ MPa}\) and \(\sigma_{\text{net}}^{\text{max}2} = 196 \text{ MPa}\), with an asymmetry factor \(R = 0\), at a frequency \(f = 3 \text{ Hz}\). The results of fatigue tests are shown in Figure 2.

Figure 2 shows that for the limits of V95 alloy limited endurance and confidence intervals (the confidence probability \(P = 0.95\)) of the material correspond to those described in [16, p. 135]. The average durability values at the studied loading levels of the V95 alloy are \(1.1 \times 10^5\) and \(4.5 \times 10^4\) cycles at \(\sigma_{\text{net}}^{\text{max}1} = 157 \text{ MPa}\) and \(\sigma_{\text{net}}^{\text{max}2} = 196 \text{ MPa}\), respectively.

![Figure 2](image_url)

**Figure 2.** Effect of metal processing in creep on endurance. Δ for the alloy V95; O for the alloy V-1461; —— for the confidence interval.
For the V-1461 alloy with a stress level $\sigma_{\text{net}1}^{\text{max}} = 157 \text{ MPa}$, as follows from [3], the limit of limited endurance is in the range of $1.6 \times 10^5 \div 2.5 \times 10^5$ cycles. However, the figure shows that the cyclic durability at $\sigma_{\text{net}1}^{\text{max}} = 157 \text{ MPa}$ has a significant scattering: from $1.6 \times 10^5$ to $10^6$ cycles. Moreover, more than 30% of samples at this level ($\sigma_{\text{net}1}^{\text{max}} = 157 \text{ MPa}$) did not collapse. The average durability values of the V-1461 alloy: $4.5 \times 10^5$ and $8.6 \times 10^4$ at $\sigma_{\text{net}1}^{\text{max}} = 157 \text{ MPa}$ and $\sigma_{\text{net}2}^{\text{max}} = 196 \text{ MPa}$, respectively.

Comparative analysis of materials shows that the average values of durability at the studied loading levels of the V-1461 alloy are not less than those specified in [3] at $\sigma_{\text{net}1}^{\text{max}} = 157$, and in relation to the V95 alloy more than 4 times and 1.8 times at $\sigma_{\text{net}1}^{\text{max}}$ and $\sigma_{\text{net}2}^{\text{max}}$, respectively.

In comparison with the durability indices mentioned in [3, 16] for the V95 alloy, they did not deteriorate, and for the V-1461 alloy, an increase in the characteristics of low-cycle fatigue was obtained for samples after technological treatment more than 3 times [3].

It should be noted that the test results did not reveal the dependence of the durability of the samples on the place of cutting samples from the plate.

3.2. Metallography

Metallographic studies of the V-1461 alloy structure (Figure 3 a, b), performed in the factory laboratory, show that the structure of the material after deformation at the temperature of $120 ^\circ C$ (temperature of alloy’s ageing) is homogeneous with a larger grain than the structure of the material being deformed at $470 ^\circ C$. This shows that the deformation at elevated temperatures makes a finer grain. During forming ($470 ^\circ C$), the alloy recrystallized, and a fine-grained structure is formed, the intermetallic phases in a dispersed form are released in a large volume (Figure 3 b). The formation of uniformly distributed disperse intermetallic phases in the V-1461 alloy microstructure at $470 ^\circ C$ increases the relative elongation and decreases the yield strength [15, 17]. Moreover, it was shown in [18] that heat treatment after deformation in creep allows avoiding residual stresses in the material.

![Figure 3](image-url)

**Figure 3.** Microstructure of V-1461 alloy: a) after forming at the temperature of $120 ^\circ C$, x500; b) after forming at the temperature of $470 ^\circ C$, x500.

3.3. Comparison of molded and target surfaces

When using the MV 224 laser radar, the spatial coordinates of the characteristic points were determined on the surface of the molded plate, which made it possible to calculate the deviations of the coordinates of these characteristic points from the target (nominal) shape of the object. Analysis of
the obtained data after the formation of the plate showed good agreement, and the maximum deviations, in accordance with the control points, are in the range from 9.27 to +5.37 mm. Less than 2.5% of the plate area is deformed with a deviation from the theoretical part of less than 9.27 mm. More than 80% of the plate area is deformed with a deviation of less than 1 mm [11].

4. Conclusions
1. Ultimate stresses for the V-1461 and V95 alloys are determined and verified by fatigue tests within the accelerated method.
2. Fatigue tests have established that the forming of plates in creep does not impair their resistance to fatigue.
3. Comparative testing of alloys shows that V-1461 has higher fatigue characteristics.
4. The example of the V-1461 alloy shows that forming at $T = 470^\circ$C makes it possible to obtain a structure with a smaller grain with respect to the initial state.

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