Determinaton of optimum parameters of the technological process for plates forming from V95 and V-1461 alloys in creep applied in aircrafts constructed by “Sukhoi design bureau”

G A Raevskaya¹, K Zakharchenko ²,³, A Larichkin ²,⁴

¹Scientific Technical Center "NTC-Polzuchest", Novosibirsk, Russia
²Institute of Hydrodynamics named after M. A. Lavrentyev, SB RAS
³Novosibirsk, Russia
⁴Novosibirsk State Technical University, Novosibirsk, Russia

E-mail: polsutchest@mail.ru

Abstract. The research is devoted to the scientific justification of metal processing by pressure with the help of thick monolithic plates forming (thickness 40 mm) from the V95 (analog 7475) (Al-Zn-Mg-Cu) and V-1461 (analog 2099) (Al-Cu-Li-Zn) alloys in creep and close-to-superplasticity. Optimum parameters of the technological process of plate forming are described. The effect of temperature on the magnitude of mechanical stresses (relaxation) during the tests of materials on pure bending is experimentally determined. Forming of thick plates (40 mm) on the UFP-IM unit, and the control of the obtained surface, in comparison with the given electronic model, made it possible to experimentally determine the time and number of forming stages. Mechanical properties of the material after the technological process and heat treatment are preliminary evaluated. The efficiency of using the obtained parameters of the technological process and treatment of metals by pressure in such methods in general is shown.

1. Introduction

Since the middle of the 20th century the high-strength V95och aluminum alloy (analog of 7475) has traditionally become the main material to manufacture power elements of the airframe. However, in recent years, the prospect of using a high-strength aluminum-lithium alloy of the V-1461 grade (analog of 2099) instead of V95och in the design of new aircrafts has been widely studied [1]. The mechanical properties of V-1461 exceed those of V95och: the density is 25% lower; modulus of elasticity – 9% higher; specific strength - 11% higher; yield strength - 14% higher; heat and corrosion resistance - 1.5-2 times higher [2].

One of the main objectives of the aviation industry development is to reduce the weight of an aircraft. It is possible to solve this problem in two ways: 1 – apply parts made from aluminum alloys of reduced density, doped with lithium, each per cent of which reduces the density by 3% and increases the modulus of elasticity by 6% [1, 3, 4]; 2) apply creep and close-to-superplasticity processes in the metals treatment by pressure, which ensures the resource conservation. This makes it possible to reduce the construction weight [5].
Today Russian aviation plants are experienced in obtaining a number of structural elements due to irreversible creep deformations developing in time at elevated temperatures [6]. Metal treatment under pressure in creep is a new technology of deformation of monolithic panels with large thickness (more than 20 mm) in the panel of double Gaussian curvature. This forming method was developed by the Novosibirsk branch of NIAT (National Institute of Aviation Technologies) with the participation of Institute of Hydrodynamics named after M. A. Lavrentyev SB RAS and Novosibirsk Aircraft Plant named after Chkalov - a branch of PJSC Sukhoi Company [7-9].

The technological process of forming in creep and in close-to-superplasticity is implemented at the UFP-1M unit, which provides the specified accuracy of the product (Figure 1).

The purpose of the research is to scientifically justify the forming modes in creep and verify the conformity of the mechanical properties of the plate material after forming.

2. Samples, equipment and method

2.1. Determination of material parameters

In order to determine the optimum temperatures and efforts for plates forming, samples in the form of beams of rectangular section (8x19x300 mm) were used, cut from the plate, milled. The samples were deformed by pure bending to the values of the deflection of 23.5-26 mm on the base of 290 mm by applying a constant bending moment over the length of the sample. The maximum bending moment is 30000 kg·mm. The design of the equipment completely eliminates the loss of the active bending moment, the scheme is given in [11]. The test temperature of the samples is constant in time; the test temperature was in the range from 360 to 470 °C.

The pure bend ensures uniform heating of the samples to a specified temperature, a different loading level, an automatic heating rate, and control of the loading, deflection, and temperature.

The plate forming in creep was carried out at the UFP-1M unit.

2.2. The technological process of forming a plate of complex geometry

The technological process of plate forming (1800x800x40 mm) in creep at the UFP-1M unit is a method of deformation without deformation hardening. Forming is carried out by moving a multitude of punches (rods), the ends of which form a discrete surface of the matrix. The movements of each rod are set individually by a computer program using servo drivers. Such a scheme of equipment eliminates the need for having an individual matrix for each part, and makes the unit universal due to the possibility of adjusting the system to a given curvature.

Slow mode with a given kinematics of deformation of the workpiece makes it possible to reduce the forming efforts due to irreversible creep deformation of the material and to operatively control the technological process. The whole process of deformation lasted no more than 30 minutes, then the stress was relaxed for 30 minutes at a given temperature, after which the heating was switched off, and the cooling was slow.

Heat treatment of formed plates included hardening and ageing; the modes are given in [9].

The conformance of the surface of the formed plates to the specified theoretical model was controlled by means of a contactless coordinate measuring system based on a laser radar MV 224. The measurement error for distances up to 5 meters does not exceed 22.5 μm.
The tensile-test after these technological operations was carried out on the Zwick / Roell Z100 unit at the Institute of Geology and Mineralogy SB RAS. The diameter of the samples is 10 mm, the base for deformation measurements is 70 mm.

3. Main results

3.1. Obtaining the parameters of the creep model

Figure 2 shows the relaxation curves of the maximum stress in rectangular beams (a) made from the V-1461T alloy and (b) from the V95 alloy for different temperatures. It follows that with increasing temperature the value of the maximum stress drops.

![Figure 2](image)

**Figure 2.** Dependence of stress on time in a rectangular beam (a) made from the V-1461 alloy and (b) made from the V95och2 alloy in the relaxation tests for different temperatures: (a) 1 - 420 °C, 2-430 °C, 3-440 °C, 4 - 450 °C, 5 - 460 °C, 6 - 470 °C, 7 - 480 °C; (b) 1 - 360 °C; 2 - 380 °C; 3, 4 - 410 °C; 5 - 420 °C, 6 - 430 °C.

It is possible to determine the parameters of the steady-state creep model from the stress relaxation diagrams. We take the analogue of the Maxwell model to describe the material - the material model is a serially connected spring and a damper: the elastic behavior of the material is modeled by a spring, so the relationship between stress and deformation is written \( \sigma = E \varepsilon \), here \( \varepsilon \) is the elastic deformation, \( E \) is the elastic modulus, \( \sigma \) - stress. The inelastic behavior of the material is modeled by a damper as a power function of relationship of deformation rate and stress: \( \dot{\varepsilon} = B \sigma^{n-1} \), here \( \dot{\varepsilon} \) -
creep rate, $B_A$ and $n$ - parameters of the steady-state creep model. A refined model taking into account microstresses and damage was proposed in [12] for the transient creep under changing loads.

Since the total deformation for the Maxwell model is the sum of the elastic and inelastic deformation $\varepsilon = \varepsilon_e + \varepsilon_i$, then the relaxation process can be written as $\dot{\varepsilon}_e + \dot{\varepsilon}_i = 0$. Thus, we obtain the equation for stress: \[ \frac{d\sigma(t)}{dt} + E(T)B_A(T)\sigma(t)^{n(T)-1} = 0. \] The initial condition $\sigma(t=0) = \sigma_0(T)$. Here $T$ - temperature. The solution is
\[ \sigma(t) = \left( \sigma_0(T)^{2-n(T)} - (2-n(T))E(T)B_A(T)(t-t_0(T)) \right)^{\frac{1}{2-n(T)}}. \]
Then using the least squares method the values of $n$ and $B_A$ were determined for each temperature. Figure 2 shows the curves (1) for each temperature.

| Table 1. Model parameters for V-1461T1 at different temperatures |
|----------------------|------------------|-----------------|-----------------|
| $T$, °C             | $B_A$, (kgf mm$^{-2}$) $^n$ h$^{-1}$ | $n$             | $E$, (kgf mm$^2$) | $\sigma_{\text{max}}$, (kgf mm$^2$) |
| 420                 | 7.77·10$^{-7}$   | 7.67            | 6981.3          | 5.05            |
| 430                 | 8.36·10$^{-7}$   | 8.60            | 4719.0          | 4.09            |
| 440                 | 2.98·10$^{-7}$   | 9.76            | 4408.9          | 3.81            |
| 450                 | 7.15·10$^{-9}$   | 16.76           | 4128.4          | 3.11            |
| 460                 | 5.15·10$^{-7}$   | 12.18           | 3931.7          | 3.15            |
| 470                 | 5.80·10$^{-5}$   | 11.55           | 1902.1          | 2.26            |
| 480                 | 6.87·10$^{-4}$   | 10.54           | 1840.2          | 1.79            |

| Table 2. Model parameters for V95ochT2 at different temperatures |
|----------------------|------------------|-----------------|-----------------|
| $T$, °C             | $B_A$, (kgf mm$^{-2}$) $^n$ h$^{-1}$ | $n$             | $E$, (kgf mm$^2$) | $\sigma_{\text{max}}$, (kgf mm$^2$) |
| 360                 | 3.75·10$^{-7}$   | 7.71            | 4250.3          | 6.83            |
| 380                 | 4.02·10$^{-7}$   | 8.42            | 6273.3          | 6.17            |
| 410                 | 3.80·10$^{-6}$   | 7.54            | 5952.0          | 4.50            |
| 410                 | 9.15·10$^{-7}$   | 10.01           | 5560.0          | 3.83            |
| 420                 | 6.31·10$^{-7}$   | 12.02           | 4279.9          | 3.39            |
| 430                 | 2.00·10$^{-5}$   | 10.50           | 4575.7          | 2.83            |

Tables 1 and 2 show the values of the parameters $B_A$ and $n$ depending on temperature, obtained on the basis of equation (1) for V-1461T2 and V95ochT2, respectively. The values of the modulus of elasticity and maximum effort are also given depending on temperatures, determined under the experimental data. Thus, the data on the relaxation of rectangular beams give the values of the creep model. The optimum temperature for forming a thick panel made from V-1461T1 was chosen to be $T = 470$ °C, and for V95ochT2 - $T = 420$ °C.

3.2. Comparison of the molded and target surfaces
The laser radar MV 224 allows determining the spatial coordinates of the characteristic points 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 shape of the object. The analysis of the obtained data after plate forming made from V95 showed compliance; the maximum deviations, in accordance with the control points, are in the range from -9.27 to + 5.37 mm (Figure 3). Less than 2.5% of the plate is
deformed with a deviation from the theory of less than 9.27 mm. More than 80% of the plate is deformed with a deviation of less than 1 mm.

Figure 3. (a) The model of the required panel (theory). (b) Deviations of the obtained surface from the surface specified in the theoretical model

3.3. Mechanical properties of samples from plates after forming

Table 3 shows the mechanical properties of samples from plates made from V95ochT2 after forming and heat treatment.

Samples cut both in the direction of rolling and across have practically the same values of the tensile strength \( \sigma_B \) and the yield strength \( \sigma_{0,2} \) with minimum scatter of the experimental data.

| Alloy, conditions | \( \sigma_B \) (kgf mm\(^{-2}\)) | \( \sigma_{0,2} \) (kgf mm\(^{-2}\)) | \( \delta \), % | \( E \), (kgf mm\(^{-2}\)) |
|------------------|---------------------|---------------------|-------------|------------------|
| V95ochT2         | 49,95               | 42,81               | 9,0         | 7553,5           |

4. Discussion

The optimum temperature for V95 is the annealing temperature \( (T = 420 ^\circ C) \), and for V-1461 - the plate rolling temperature \( (T = 470 ^\circ C) \) [10]. A natural question may arise: will high temperatures of 420 \(^\circ\) C and 470 \(^\circ\) C lead to an increase in grain in the material structure? This temperature and the holding time (30-40 min) make it possible to avoid the process of collective recrystallization - the formation of a coarse crystal structure in the abovementioned alloys.

It should be noted that the described technical process of forming thick panels includes the subsequent heat treatment of the product - quenching and ageing, which means adding one more technical operation, compared with molding at the ageing temperature [13] and affects the mechanical properties of the materials positively (no more than two quenching are allowed P1-1.2.699-2007).
The choice of optimal modes of forming is dictated not only by the properties of materials, thickness of the samples (40 mm), but also by the power capabilities of the unit.

5. Conclusion
Optimum temperatures for forming thick plates made from V-1461 and V95 are 470 °C and 420 °C, respectively. It has been established that within 30-40 minutes of the process the following characteristics are ensured: steady creep, no springing, and almost complete relaxation of stresses. The experimental relaxation diagrams for various temperatures give the parameters of the steady-state creep model.

A program for the step-by-step forming plates has been developed, which excludes the possibility of a coarse-crystal structure development in the material, as well as wedging of the rods of the unit.

It is shown that the results of tensile tests for samples made from V95och2 after forming correspond to those indicated in [14].

Thus, the conducted research showed that after forming the plate at the UFP-1M unit, heat treatment and subsequent milling, it is possible to obtain a product of high quality with low material consumption.

Acknowledgments
This work was partially supported by the Russian Foundation for Basic Research (project codes 16-08-00483 A, 15-01-07631 A).

References
[1] Ogolodkov M 2013 Regularities of alteration structure and properties of rolled semi-finished products from alloy V-1461, depending on technological parameters of production and heat treatment Abstract. VIAM. Moscow p 27
[2] Khokhlatova L, Kolobnev N, Ogolodkov M, Filatov A and Popova Yu 2014 All materials. Encyclopedic reference book 2 16 - 22
[3] Khokhlatova L, Kolobnev N, Ogolodkov M, Lukina E and Sbitneva S 2012 Metallurgy and heat treatment of metals 6 20 - 4
[4] Khokhlatova L, Ogolodkov M and Ponomarev E 2012 Metallurgy of machine building 3 22 - 6
[5] Gorev B, Klopotov I, Raevskaya G and Sosnin O 1980 j. Appl. mech. Tech. phys. 5 pp 185 - 91
[6] Holman M 1989 Journal of Mechanical Working Technology 20 477-88
[7] Miodushevsky P, Raevskaya G and Sosnin O 1992 The method of forming parts and device for its implementation Patent for invention RUS 2056197 6 p
[8] Klopotov I, Lyubasheskayia I, Raevskaya G, Rublevsky L and Sosnin 2002 O Molding device Patent for the invention RUS 2251464 22 07
[9] Larichkin A, Gorev B, Zakharchenko K, Kapustin V 2017 Tekhnologiya Mashinostroeniya 3 5 - 9
[10] Yerisov Y, Grenchnikov F and Ogolodkov M 2015 News of higher educational institutions Non-ferrous metallurgy 6 36 - 42
[11] Kolodezev V, Gorev B, Larichkin A and Shevtsova L 2017 Tekhnologiya Mashinostroeniya 2 11 - 16
[12] Shutov A V, Larichkin A and Shutov V A 2017 Angew Math. Mech. DOI 10.1002/zamm.201600286 pp 1–17
[13] Troyanov V, Uksusnikov A, Senatorova O and Pushin V 2011 About the possibility of obtaining thermostable high-strength alloys of the Al-Zn-Mg-Cu system with nano-phase separation 1 121. In the book: Second Moscow readings on problems of strength of materials, dedicated to the 80th anniversary of the birth of academician of the Russian Academy of Sciences Yu.A. Osipyana theses of the reports p 152
[14] Fridylander I, Senatorova O, Tkachenko E, Molostova I 2008 All materials Encyclopedic reference book 8 17-21