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Influence of the creep ageing process on the fatigue properties of components from V95pchT2 (analog 7175T76) and V95ochT2 (analog 7475) aluminium alloys

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Abstract. Influence of conditions of technological process of forming thick panels of a given geometry on fatigue limit of flat specimens from the V95ochT2 and V95pchT2 (analogues 7475 and 7175T76) alloys (Al-Mg-Cu-Zn) has been analysed. The process has been simulated experimentally on flat samples for temperatures 20, 165 and 420°C. The process includes: non-elastic strain in the range $10^{-5}$ - $10^{-2}$ s⁻¹ up to 2% of total strain, followed by heat treatment according to T2 mode (quenching and aging). Fatigue life tests were carried out both on solid samples and on samples with a hole. It has been shown that resistance to fatigue of the observed alloys after forming at the annealing temperature (420°C) is comparable to the basic material resistance to fatigue. Meso-structure analysis showed absence of stress in grains. It is established that, on average, the shape of the grains is the same for a series of samples for different temperatures and loading rates. The results of testing samples with a hole showed that fatigue limit slightly decreases in samples which were previously deformed at (420°C), with respect to the durability of samples from the material in basic state. With an increase in rate of pre-strain, the relative number of cycles before destruction occurs increased.

1. Introduction

Strain ageing combined with CAF (creep age forming) is an interesting and strongly needed technology in aviation. This production method by forming of 7XXX aluminum alloys thin plates (not more than 15-20 mm) has proved to have the required accuracy in production of panels with double curvature without finishing works and preserve their long service life. These plates are used as wing skins and other elements of the airframe. Existing technologies require forming of panels at temperatures not exceeding the ageing temperature of the material. Obtaining of the target form of thick plates (more than 40 mm) by CAF is more complicated for technical reasons since it requires heavy presses in addition to heating.
2. Idea and method

A well-known CAF method (creep age forming) [1] includes two processes: creep and heat treatment (ageing), which depends on time and temperature. This method is actively used in the aerospace industry to form big panels with a complex curvature. For example, the B1B and Hawk bombers, the executive jet Gulfstream G-IV and the commercial Airbus jets A330 and A340, as well as the A380 [2, 3]. However, there are no examples of the reinforced panels made from the thick plates. Compared with other processes, CAF results in lower residual stresses leading to higher fatigue characteristics [2].

This research was conducted to address the problem of forming solid or ribbed plates of the V95ochT2 alloy (Al-Mg-Cu-Zn) (analog 7475) V95pchT2 alloy (analog 7175T76) for the jet industry. It is possible to make a complex geometry of the initially rectangular plate by using a multi-channel forming module (Figure 1).

The final product is made from the initial flat plate deformed in the plug-in equipment. Figure 1a shows the form and kinematics of the experimental multi-channel forming module. Here, 1 – plate, 2 – oven.

The module is designed for the accurate forming of smooth and ribbed large plates of single and double curvature in creep or close to superplasticity. The plates are deformed by the movement of two discretely set rod systems arranged oppositely to the detail’s surface.

For reinforced panels, rods of the hydraulic puncheons are set against intersection of edges, for smooth – in rows within the panels’ width. Swivel heads are placed at the end of the rods to form the workpiece without dents and corrugating. The movement of each rod is set individually by a computer program using a stepper motor that allows forming the details of double curvature in one technological step. Combined forming and heat treatment of the material in the slow strain modes due to irreversible creep strain significantly reduce forming forces and make the technological process cost effective.

Most of the existing technological solutions use load distribution with the constant rate of rod or snap movement. It should be noted that strain at the constant rate of rods movement and at individual rates of each rod movement leads to different results. Figure 2 shows the scheme of strain of a rectangular plate into the saddle surface. Figure 2a shows how the workpiece is first bent in the cylindrical surface. Then geometric buckling occurs at further bending along the element of cylinder to form corrugations.

Figure 2b shows bending of a plate from the initial to the final shape in two main directions simultaneously throughout the entire strain process. This changes the shape of a workpiece without buckling and may be either continuous or divided into a series of intermediate stages depending on the complexity of the product.
The technology of forming is based on the solution of the inverse problem of inelastic strain of the body in creep, followed by elastic springback. The essence of the problem lies in defining the force and shape of the equipment to form the workpiece, which will provide the specified curvature after removal of the load. The mathematical apparatus for solving such problems is given in [4]. The complexity of these problems is connected with the substantial anisotropy of the creep properties of the workpiece, as well as with the strength difference (SD) effect (tension-compression asymmetry) of the material.

In [5] creep phenomenological models are presented which were introduced in FEM to calculate the springback of the constructions after CAF. The plates with a constant thickness are considered. In [6] constitutive equations were established for AA7010 which take into account the creep effect and precipitation hardening. These equations are implemented in FEM to simulate the forming of thick plates of double curvature [7]. The authors report that it is possible to estimate the influence of the thickness of the plate and the process time on the springback [8].

In [9], the numerical solution of the problem of forming an element of double curvature in creep is given, taking into account the strength difference (SD) effect of the material. Leaving it aside leads to a difference between the calculated bending of the structure and that which is observed experimentally. In [10] the solution to the problem of torsion of the plate by permanent moment is given taking into account anisotropic properties of the material. It is mentioned that direction at the angle of 45° to the normal of the anisotropic plate is the least resisting to the creep. In [11] an anisotropic finite strain creep model was proposed for CAF applications.

The answer to the question about the influence of the characteristics of the process - rate and temperature of the workpiece forming - on the fatigue life of the formed structures is important for a modern aircraft manufacturing. The forming parameters are chosen in connection with the requirements to the final physical and mechanical properties of the material. This leads to the question: how long is the fatigue life of a product following this process?

To answer this question we reconstructed the technological conditions of forming in the laboratory with samples of V95ochT2 (plate \( h = 15 \) mm) and V95pchT2 (plate \( h = 36 \) mm) (analogues 7475 and 7175T76) alloys (Al-Mg-Cu-Zn). Flat samples from V95ochT2 (4 mm thick, 10 mm wide) were cut longitudinally and transversely to plate rolling direction, and flat samples with hole from V95pchT2 (4 mm thick, 36 mm wide) were cut longitudinally to plate rolling direction.

Test algorithm for samples from V95ochT2 is as follows: the samples divided into three series I, II and III were pre-strained up to 2% of tensile deformation at three different temperatures (\( T = 20 \) °C, 165°C, 420°C), respectively. The temperature for the II series is the temperature of the second stage of artificial ageing (T2 mode), and the temperature for the III series corresponds to the annealing temperature [12, 13]. The tests were conducted at Zwick Roell Z100, and for each temperature the strain rate changed (from \( 10^{-5} \) to \( 8 \cdot 10^{-2} \) s\(^{-1}\)). The samples were then exposed to heat treatment at the T2 mode (quenching in water at 470 °C and ageing at 115 and 165°C during the day). Test algorithm for samples from V95pchT2 was the same but only for \( T = 420 \) °C, and holes (6 mm diameter of the hole) were drilled after heat treatment in the middle of samples.

The flat samples treated in this way were tested for fatigue life. Stress for fatigue tests was determined by methods [12, 13], including:
- in-situ measurement of strain characteristics allowing to describe the laws of inelastic strain of the material;
- in-situ measurement of the dissipative heating temperature of the sample surface, indicating the beginning of irreversible effects in the material.

A fatigue life test was performed at room temperature (frequency 10 Hz, amplitude of cycle \( \sigma_{\text{max}} = 250 \) MPa (for V95ochT2) and \( \sigma_{\text{max}} = 157 \) MPa (for V95pchT2), \( \sigma_{\text{min}} = 0 \) MPa) on an Instron 8801 fatigue testing machine.

The microstructure of the material was studied by scanning electron microscopy (on a Hitachi S-3400N instrument).
3. Results

Figure 3. Results for V95ochT2: (a) - Dependence of $\sigma_{0,2}$ on the pre-strain rate; (b) - dependence of number of cycles before destruction from the pre-strain rate for different series of tests.

The experiments have shown that the yield strength at higher temperature is almost 5 times smaller than at room temperature, and it rises with increasing pre-strain rate. Figure 3(a) shows the dependence of $\sigma_{0,2}$ on the pre-strain rate at different temperatures. Figure 3(a) shows the results for V95ochT2 samples: dependence of $\sigma_{0,2}$ on the pre-strain rate for different temperatures: 1 – Series I at $T=24^{\circ}\text{C}$; 2 – Series II first direction at $T=165^{\circ}\text{C}$; 3 – Series II orthogonal direction at $T=165^{\circ}\text{C}$; 4 – Series III orthogonal direction at $T=420^{\circ}\text{C}$. Figure 3(b) shows the number of cycles of the pre-strain for different temperatures. We can see that the fracture life for series I ($20^{\circ}\text{C}$) and III ($420^{\circ}\text{C}$) increases with increasing pre-strain rate, and for series II ($165^{\circ}\text{C}$) this is decreasing.

Figure 4 shows values of relative fatigue limit as a function of the pre-strain rate for samples of the V95pchT2 alloy. Here, $N$ is the number of cycles before fracture of the samples previously deformed at $420^{\circ}\text{C}$, $N_0$ is the fatigue limit for the samples in the base state. Fatigue test of V95pchT2 alloy were on samples with hole.

Figure 5 shows the microstructure of the samples from V95ochT2 after stretching up to 2% strain at different temperatures and heat treatment. On Figure 5 (a, c, e, g) the images of grains are presented, and on (b, d, f, h) the images of microstresses are presented. Pre-strain temperatures are: (a), (b) $T=24^{\circ}\text{C}$; (c), (d) $T=165^{\circ}\text{C}$; (e), (f) $T=420^{\circ}\text{C}$; (g), (h) no pre-strain – the base material;
Figure 5. Microstructure of V95ochT2 samples after pre-strain up to 2% of total strain at different temperatures. Pre-strain temperatures are: (a), (b) $T=24^\circ$C; (c), (d) $T=165^\circ$C; (e), (f) $T=420^\circ$C; (g), (h) no pre-strain – the base material.

Analysis of microstructure images showed that the change in grain structure of the material after pre-strain and heat treatment (series I, II, III) did not occur, grain size did not change in comparison with the base material; residual stresses of the second kind in deformed samples (I, II, and III series) after heat treatment are absent.
4. Conclusion
These results allow determining optimal temperature and strain rates for the technological forming of the parts with complex geometry produced within a single cycle. The optimality criterion is a high fatigue limit of the product.

It is shown that the fatigue limit of V95ochT2 after pre-strain at the ageing temperature of 165°C with subsequent heat treatment becomes higher with the decreasing pre-strain rate (Figure 3b).

It is shown experimentally that at increasing strain rate in series III the trend to increase the number of cycles before destruction has been observed. In series I there is a trend to reduce the number of cycles before destruction, which correlates with the results of the forming method proposed in [14].

Pre-strain of the samples at annealing temperature (420°C) and a strain rate of $10^{-2}$ s$^{-1}$, followed by heat treatment in the T2 mode does not reduce the resistance to fatigue as compared with the samples deformed at 20°C.

5. Discussion
A number of modern works devoted to CAF at forming products from the constructional 7XXX aluminum alloys is worth mentioning.

The research on influence of pre-strain of the sheets made of the 7475 alloy on CAF is close to the research given in this article [15]. The authors say that the strength property varies by a low-to-peak-to-low manner as the increase of the deformation degree, and the radius-thickness ratio of the peak strength maintains a constant.

Some foreign authors justified the method of forming plates made of the Al-Zn-Mg-Cu alloy by CAF methods at the ageing temperature (at 165°C for 18 h) [16]. The authors show that the relationship between initial temper and CAF formability is investigated. Three tempers are selected as the initial tempers in CAF, viz., solution, retrogression and re-solution. The CAF formability of this alloy with initial temper of retrogression is the best, and the creep strain of the retrogression tempered specimen after creep aging of 18 h is about 1.21 and 1.34 times than that of the solution and the re-solution tempered specimens, respectively.

After the analysis of the relevant works it can be concluded that forming at the ageing temperature is commonly used for thin plates made from the V95ochT2 and V95pchT2 alloys since in this case forming and ageing are combined in one process.

In [17] forming and defining of the AA7475 ribbed wing panel springback (T73) in a vacuum bag and an autoclave at the temperature of ageing are considered (the recommended overageing procedure consists in a two step cycle of 6 to 8 hours at 121°C followed by 24 to 30 hours at 163 °C). However, the authors refer to the results of research on the influence of the effect of Retrogression and re-ageing treatments on the resistance to cracks for the materials of 7XXX series (AA7050 and AA7150), but different from V95ochT2 (7475).

The authors consider forming of a thin panel at the temperature of ageing, and they say that the magnitude of the springback can reach about 40 up to 70% of the imposed initial curvature. Such a high level of the springback can be reduced by forming at the annealing temperature. Also forming at the annealing temperature can significantly reduce the efforts and enables almost complete relaxation of the internal stresses; however, it adds two technological procedures: water quenching and ageing of the material. This article answers the question about the optimal strain mode, which allows forming thick panels and preserving their long service life.

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