Preparation of samples for investigating the durability of aluminum alloy D16AM after deformation and magnetic-pulse processing

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Abstract. The analysis of accidental operational impact damage to the wing structure, which is experienced by the aircraft structure during its service life, is necessary to solve safety problems. The task of this work is to build a realistic picture of accidental mechanical damage on an aircraft wing made of D16AM aluminum alloy. Acts of technical condition research when extending resources and periodically confirming the airworthiness of sample parts, reports of technical services and repair plants for documenting the technical condition of aircraft. The work is devoted to the study of parts’ cyclic durability made of aluminum alloy D16AM in tests for complex mechanical damage. The proposed solutions are performed at two levels of the magnetic-pulse pressure amplitude (P₁ = 32MPa and P₂ = 20MPa) by the ANSYS / LS-DYNA software. The influence of various types of stress state on cyclic strength is an urgent research area in aircraft maintenance and repair service.

1. Introduction
One of the most effective metal forming types is magnetic-pulsed loading (MPL) in sheet stamping, which allows obtaining flat and spatial parts of a wide variety of sizes and configurations with a high metal utilization rate at a given strength, rigidity and also provides high labor productivity, especially in conditions of aircraft serial production. Electromagnetic forming is increasingly finding its application in the reshaping of sheet metal for use in aircraft maintenance because of its efficiency in forming aluminum and other materials with low permeability [1–2]. Due to the high rate deformation, the reforming ability of the material can be increased by electromagnetic forming, in accordance with the phenomena of corrugation and springback can be minimized by the induced high-speed collision of the sheet metal with the die, which affects the adaptability, resulting in good quality of the workpiece forming [3–5].

2. Materials and Methods

2.1. Experiment setup
Mechanical stress testing is the most common type of tests for evaluating the mechanical properties of metals and alloys. It can be easily analyzed, it allows one to determine several important mechanical characteristics at once according to the results of one experiment [6]. The purpose of our simulation work is to prove that through MPL, it is possible to extend the service life and durability of aircraft parts.
by reversing the damaged parts, returning long-used and damaged parts refurbished to the workplace. Under mechanical stress, the part is subjected to cyclic loading, which leads to a dislocation of the integrity and damage to the structure of the aircraft parts. A specimen in the form of dog-bone made of D16AM aluminum alloy was taken as a sample for the study [7–9] as shown in figure 1.

![Figure 1](image1.png)

**Figure 1.** A flat dog-bone specimen in its initial position.

Figure 2 shows a scheme of the mechanical damage action with a punch impact velocity of 40 $m/s$ in a negative uniaxial position $Z$-axis.

![Figure 2](image2.png)

**Figure 2.** Scheme of the mechanical damage action of the punch on the specimen: 1 – punch; 2 – holder with a clamp; 3 – die; 4 – damaged part.

2.2. Analysis of the results
In order to overcome the problems of mechanical damage loading during the stretching of the sample, a two-stage of electromagnetic forming process has been proposed to eliminate the various natures of mechanical influences. At the first stage, a coil of uniform pressure with a clamp was used to straighten a concave sample with a microrelief, with an applied force $Q_1 = 25kN$. At the second important stage, to make the sample smoother and more even, the clamp was used repeatedly with force of $Q_2 = 50kN$ and with a decrease in electromagnetic pressure than in the first stage. Cyclic durability is influenced by various factors, including loading frequency and type of stress-strain state.
2.2.1. The first stage of straightening the sample by magnetic-pulse loading

![Image](a) (b)

**Figure 3.** Plastic deformation of the sample at the stage of pulse-straightening: a – 0 sec., b – 7.5e-5 sec.

At the stage of straightening the sample by magnetic-pulse process, measuring the thickness at the control zones showed that the greatest thinning of the deformable solid occurred in the end zone (1) with a thickness of 1.43 mm, in the middle zone (2) the thickness was 1.52 mm and at the end zone (3) thickness was 1.44 mm (Fig. 4).

![Image](end zone 1 middle zone 2 end zone 3)

**Figure 4.** Change in the material thickness in the control zones during the straightening stage.

2.2.2. The second stage of alignment the sample by magnetic-pulse loading

Figure 5 shows the scheme of electromagnetic loading at the second stage of sample alignment.

![Image](grid scheme of electromagnetic loading)

**Figure 5.** Grid scheme of electromagnetic loading at the alignment stage: 1 – plate; 2 – straightened sample from stage # 1; 3 – coil; 4 – holder.
At the second stage of the sample alignment by magnetic-pulse process, measuring the thickness at the control zones showed that the greatest thinning occurred in the end zone (1), the thickness was 1.41 mm, in the middle zone (2) the thickness was 1.49 mm and along the end zone (3) it was 1.42 mm (Fig. 7).

Figure 8 shows a graph of the total plastic deformation for the two magnetic-pulse stages: for the end zone (1), the deformation was 15%, for the middle zone (2) it was 6.2%, and for the end zone (3) it was about 15.5%. It is observed that in the end zone (1) the deformation increased by 2%, and in the middle zone (2) it increased by 2.2%, and in the end zone (3) it increased by 3.5%. The efficiency of converting pulsed-magnetic pressure into pulsed-technological load was determined by the ratio of the maximum forces in time at the zones of the moving elements [1]. Thus, the magnetic pressure along the positive uniaxial position Z-axis calculated by the Equation (1):

\[ P_z = \frac{B_z^2}{2\mu_0\mu_i} \]  

Where \( P_z \) represents the magnetic pressure along the Z-direction, \( B_z \) represents the magnetic field intensity along the X-direction and \( \mu_i \) represents the relative magnetic permeability of the aluminum alloy D16AM.
Figure 8. The total plastic deformation of the samples in the control zones: (end zone 1, middle zone 2, end zone 3) for two magnetic-pulse loading stages.

The results of numerical simulation of mechanical damage impact and the reverse stepwise of 2-step magnetic-pulse loading on specimens to obtain parts of a straightened and aligned shape were summarized in the form of a nomogram [6, 7]. Nomogram for determining the optimal pressure amplitude (P) depending on the dynamic yield strength $Y_{ow}$ of the aluminum alloy D16AM, geometric parameter of the specimen thickness $\delta_0$ and the deflection height $h_{def}$ for the sheet metal reshaping process are presented in figure 9.

Figure 9. Nomogram for determining the optimal pressure amplitude (P) of the PMF for obtaining parts of a straightened and aligned shape with various parameters $Y_{ow}$, $\delta_0$, $h_{def}$.

3. Results

Thus, the above studies allow us to draw the following conclusions:

1) Obviously, the electromagnetic process has a lot of promising uses, which are useful not only in the production of aircraft parts, but also in the repair and maintenance service, which extends their durability and gives new life to the parts.

2) Calculation of the thickness of a deformable solid at the final stage of defects elimination by control zones showed that the greatest thinning occurred in the end zone (1), the thickness was 1.41 mm, less than in the end zone (3) by 0.01 mm, and by 0.08 mm less than in the middle zone (2).
3) The calculation of the total plastic deformation from the control zones showed that the greatest deformation occurs in the end zone (3) and is estimated at 15.5%.
4) In the above outputs, it was observed that in the end zone (1) the deformation increased by 2%, and in the middle zone (2) it increased by 2.2%, and in the end zone (3) it increased by 3.5%.
5) The calculated pressure of the EM at the first stage of straightening was estimated at 32 MPa with a deformation time of 7.5e-5 sec. At the second stage of alignment, the calculated pressure decreased to 20 MPa with an increase clamping force in twice.
6) The work done on the study of the cyclic durability of aircraft parts made of aluminum alloy D16AM for complex mechanical damage loading has been tested, which is an urgent tendency in further research using magnetic-pulse loading.

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References
[1] Belyy I V, Fertik S M and Khimenko L T 1970 Electromagnetic Metal Forming Handbook (Kharkiv: Visha shkola) p 190
[2] Bogoyavlensky KN 1984 Magnetic-elastic-pulse cutting punching of thin-sheet materials: J. Forge, and Stamp. Prod. Mat. Working by Pressure (KShP) 7 12-4
[3] Woodward S, Weddeling C, Daehn G, Psyk V, Carson B and Tekkaya A E 2010 Agile Production of Sheet Metal Aviation Components Using Disposable Electromagnetic Actuators 4th Int. Conf. on High Speed Forming, March 9th – 10th 2010 Ohio, USA 35-46
[4] Li GY, Deng HK, Mao YF, Zhang X and Cui JJ 2018 Study on AA5182 aluminum sheet formability using combined quasi-static dynamic tensile processes: J. Mater. Process. Technol. (JMPT) 255 373-86
[5] Rao Y G, Nataraj M R S and Srinivas P 2019 Explicit Dynamic Analysis of Tensional & Torsional Propagations on Composite Material with Dog Bone Shaped Testing Specimen: Int. J. for Mod. Trends in Sci. and Tech. 05(08) 34-47
[6] Kurlaev N V and Ahmed Soliman M E 2020 Simulation of rift element forming by magnetic-pulse deformation: IOP Conf. Ser.: Mater. Sci. Eng. 919 022011 (Krasnoyarsk: SibGU) 6 p
[7] Kurlaev N V, Ahmed Soliman M E and Detinov M B 2021 Forming the inner flange of a rib by pulsed-magnetic field pressure: IOP Conf. Ser.: Mater. Sci. Eng. 1047 012002 (Krasnoyarsk: SibGU) 7 p
[8] Imbert J and Worswick M J 2012 Reduction of a preformed radius in aluminium sheet using electromagnetic and conventional forming: J. Mat. Proc. Tech. 212(9) 1963-72
[9] VanBenthysen R, Thibaudeau E and Kinsey BL 2013 Effect of specimen planar area on electromagnetic flanging J. Manuf. Proc. (JMP) 15 194-200