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APPLICATION OF THE STEREOMICROPHOTOGRAMMETRIC METHOD FOR THE COMPLEX STUDY OF THE AL-CU-MG ALLOYS SYSTEM

Purpose. To combine the stereophotogrammetric method for processing fracture surface images at the micro level with the results of a series of mechanical and metal fractographic studies with precision methods for scanning electron microscopy (SEM) and energy dispersive analysis (EDX) in order to determine the peculiarities and general laws of the fracture process of Al-Cu-Mg test samples.

Methodology. In this work, the mechanical properties of Al-Cu-Mg samples after mild (recrystallization) annealing and subsequent natural aging and a sample without heat treatment were experimentally determined. At the next stage, SEM-stereomicrofractographic research on fractures and their three-dimensional reconstruction from the obtained stereo images were performed. EDX studies have been performed on various parts of the samples to determine the distribution of mass percentages of elements in the study areas. A comprehensive methodology for experimental studies of Al-Cu-Mg alloys was used in this work to obtain qualitative and quantitative information on the microstructure of fractures, which consisted of the following steps: determination of the mechanical properties of samples by traditional methods of macro- and microanalysis; study on stereopairs of the microstructure of fractures by the stereophotogrammetric method; identification of the chemical composition and structure of matrix precipitation particles by energy dispersive X-ray spectroscopy (EDX analysis).

Findings. Our experiments have shown that with an increase in the time of natural aging, the hardness increases slowly and reaches a maximum hardness of 127 Hv30 after 97 hours, which does not decrease subsequently. After natural hardening, the average fracture strength increases to Rm 440.3 with a relative elongation of 21.8 %. Mechanical tests have shown that the tensile strength increases with the hardness value and, in contrast, the toughness decreases. The energy required to fracture the sample is 16 J, followed by transcrystalline cellular fracture. The precipitates have a diameter of approximately 2.5–3 microns.

Originality. Comparing the results of mechanical and metallographic studies, it can be argued that the desired properties of Al-Cu-Mg samples appear after dispersion hardening, which confirms the optimal hardening conditions. The results of the photogrammetric evaluation of samples in the micro range demonstrate the flexibility and accuracy potential of photogrammetric measurement methods and their subsequent processing, interpretation, and integration with EDX analysis to select optimal study sites.

Practical value. An integrated approach to the analysis of materials using the SEM stereomicrophotogrammetric method, mechanical and metallographic studies, and EDX analysis was tested in this work.

Keywords: *Al-Cu-Mg alloy, SEM stereo microphotogrammetry, mechanical studies, metallographic studies, EDX analysis*

Introduction. In our time of climate change and raw material shortages, the development of new energy-efficient materials plays an important role. Both from an economic point of view, due to rising prices for raw materials and energy, and from an environmental point of view, industrial and basic research is largely focused on aluminum and its alloys, in particular on the development of lightweight structures made of aluminum alloys, which are widely used in the aviation industry, defense equipment, and mechanical engineering (for example, in the form of high-strength structural parts and rivets). Despite the progressive replacement of existing structures with new materials such as glass and reinforced carbon fiber, modification of proven and classic aluminum alloys can be a promising alternative to solve growing demands, particularly in aircraft construction [1]. Due to their good mechanical properties (increased fracture toughness and crack resistance, fatigue resistance and corrosion resistance, as well as increased strength characteristics), ultrafine-grained materials with grain sizes in the submicron range have recently become increasingly important. Compared to materials with a conventional grain size, these materials are impressive for their increased strength with unchanged ductility [2], although they are not very resistant to corrosion.

The degree of influence of these microstructural features on the characteristics has not yet been determined and is the subject of current research.

Existing publications on this topic are often limited to visualization methods such as scanning electron microscopy (SEM). Although these methods give a good idea of the microstructure of the alloy state under study, it is difficult and time-consuming to characterize the entire sequence of the deposition process of experimental alloys due to the complex samples preparation.

Literature review. Many works have been devoted to the study on the structure of metastable states of Al-Cu-Mg alloys and their phase states [3, 4]. The analysis of scientific publications shows that the hardness of these alloys increases due to dispersion hardening, and the maximum hardness is achieved with partially coherent precipitation. The size, spatial distribution, and crystal structure of these precipitates have a significant impact on the mechanical properties of these alloys [5, 6]. In [7], experiments were performed using differential scanning calorimetry (DSC) technology, and measurements were made of the hardness, positron lifetime, resistivity, and microstructure of the Al-Cu-Mg alloy. The effect of Mg content on the microstructure, mechanical properties, and resistance to intercrystalline corrosion was investigated using various types of microscopy and X-ray radiation in [8]. The interest of the scientific community in the study on Al-Cu-Mg systems confirms the relevance of such research. The present work is a logical continuation of the research begun in [9, 10].

Unsolved aspects of the problem. In recent years, photogrammetric methods and systems for three-dimensional industrial metrology at the micro level have become increasingly significant, as they provide an opportunity to come closer to understanding micromechanisms and fracture problems. The reasons for this lie in the progress of digital image acquisition and processing, which have led to increased measurement accuracy, a higher degree of automation, and faster processing of the data stream. The applications of industrial microphotogrammetry vary from high-precision inspection to integrated systems in production plants.

Despite the perspective of integrating photogrammetry into scanning electron microscopy, today most researchers are limited to qualitative evaluation of SEM images. Microphotogrammetric methods do not have these disadvantages and the need for a priori apostulation of the spatial organization of the objects under study.

Aspects of the correlation between the microstructure of alloys and their performance properties have not been studied sufficiently, such as the specifics of hardening, heat resistance, heat resistance, creep, corrosion, cyclic or relaxation resistance, and environmental issues of manufacturing and use.

The purpose of this work is to combine the stereophotogrammetric method for processing fracture surface images at the micro level with the results of a series of mechanical and metal fractographic studies with precision methods for scanning electron microscopy (SEM) and energy dispersive analysis (EDX) in order to determine the peculiarities and general laws of the fracture process of Al-Cu-Mg test samples.

Methods. Visualization of fracture surfaces using a scanning electron microscope (SEM) provides high-resolution images necessary for microfractographic assessment of the mechanisms and causes of fracture. In SEM, there are various methods for obtaining spatial information about the microsurface [11, 12].

The use of the stereo photogrammetric method for materials science problems was first introduced by O. Kolednik in 1981. Numerous applications of photogrammetric methods of spatial estimation have shown the general applicability of photogrammetric methods in the microrange [13, 14].

The technique for obtaining stereo pairs in SEM consists in repeatedly imaging the same area of the sample under study, tilted at an angle (5–10°) with respect to the electron probe. However, the process of image acquisition in SEM has a number of limitations caused, in particular, by different illumination of the sample sections and some of their displacements due to the tilt of the goniometric table during the acquisition, which necessitates the correction of distortions and, as a result, the spatial information about the microsurface of the object of study is lost [15].

Therefore, it is advisable to perform mathematical modeling of total geometric distortions of SEM images.

In this work, a photogrammetric method of semi-automatic microsurface imaging in combination with the Hilger-Watts method, according to which two images are scanned synchronously, was used (Fig. 1).

A stereomodel of a micro-object can be obtained using the intersections of the corresponding rays reconstructed from two SEM images of a stereo pair that were taken from one, two or more viewing angles.

The samples, which are mounted on the goniometer table, can be rotated in the x and y axes to match the measurement position. The evaluation is performed using a digital photogrammetric station, which directly measures the image coordinates. The calculation of the three-dimensional data is based on the positions of the central projection. The resulting images are observed using the optical system of the photogrammetric station, and the measurement points are determined on the images simultaneously. Based on the collected information about the regular or irregular grid of objects in the images, three-dimensional microsurfaces can be further modeled and analyzed.

The stereoscopic evaluation of SEM images is based on the Piazzesi algorithm and is an advancement of the classical photogrammetric method [16].

Suppose that the surface of the sample on which the point $P(z, \eta, \xi)$ lies is tilted by an angle (Fig. 2), then the coordinates z, η, ξ are calculated according to the equations

$$z = \frac{(y_1 - y_2)\cos\Delta\phi + \dfrac{2y_1y_2}{d}\sin\Delta\phi}{\dfrac{1+y_1y_2}{d^2}\sin 2\Delta\phi + \dfrac{y_1 - y_2}{d}\cos 2\Delta\phi};$$

$$\xi = \frac{2d - 2z\cos\Delta\phi}{\dfrac{d}{x_1} + \dfrac{d}{x_2}};$$

$$\eta = \frac{(y_1 + y_2)\cdot(z\cos\Delta\phi - d)}{(y_1 - y_2)\sin\Delta\phi - 2d\cos\Delta\phi},$$

where x_1, y_1 are the coordinates of the point P in the non-inclined state; x_2, y_2 – coordinates of point P in the inclined state; d is the distance to the object; D is focal distance.

Let us say we have two coordinate systems: the local *x, y* coordinate system in which the sample plane lies, and the local *X, Y* coordinate system in which the image plane lies. Since only the image coordinates (*X, Y*) can be measured, the coordinates used in the equations of classical photogrammetry must first be converted to the sample plane using the equations where *M* is the magnification.

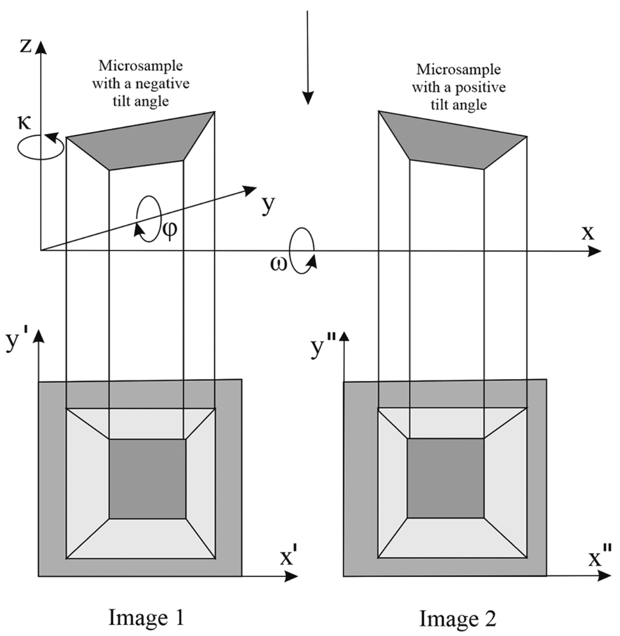

Fig. 1. The principle of stereo imaging in SEM

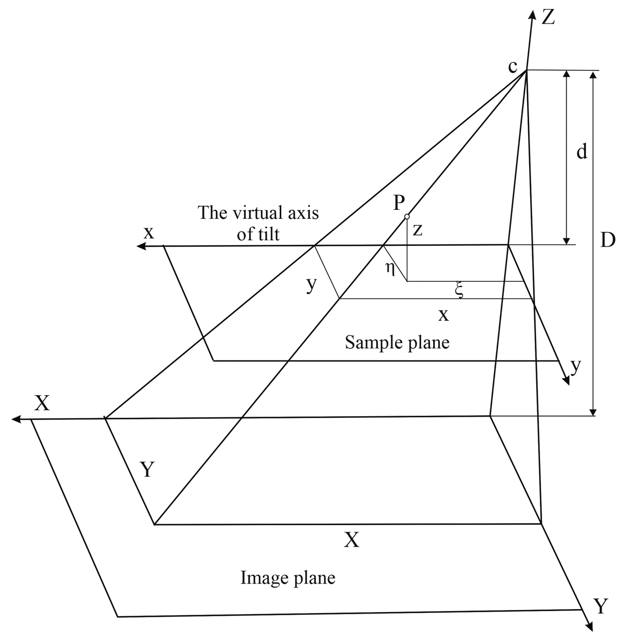

Fig. 2. Projection of a point P onto a plane

$$x_1 = \frac{X_1}{M}; \quad y_1 = \frac{Y_1}{M}.$$

The calculation of the coordinates $P(z, \eta, \xi)$ can be simplified if the displacement $Y_1 - Y_2$, called parallax, is insignificant compared to the working distance d, which occurs in the REM. In this case, the approximation equations are valid

$$z \approx \frac{(Y_1 - Y_2)\cos\Delta\phi}{M \sin 2\Delta\phi}; \qquad (1)$$

$$\xi \approx \frac{X_1}{M} \approx \frac{X_2}{M}.$$

The relative error of the approximation equation (1) when using a scanning electron microscope is less than one percent and is compensated for at medium parallaxes [17]. The process of obtaining three-dimensional data using the stereoscopic method was described by E. Erwin in [18].

For stereo images obtained from a scanning electron microscope, we apply a simplified form of the Piazzesi algorithm according to (1).

The parallax Δx was measured at homologous points (identical points) on the tilted images. The parallax of point B is determined by the difference in distances $A'B' - A''B''$. The tilt angle of the stereo images is 2α (Fig. 3).

The relative height Δz is calculated according to the following equation, which is derived from (1).

$$\Delta z = \frac{1}{2M \sin\alpha} \Delta x. \qquad (2)$$

According to (2), by multiplying the lateral resolution by, the vertical resolution can be obtained.

The dependence for the lateral resolution at 98 microns is shown in Table 1.

Thus, stereo pairs of SEM images obtained with a zero base and tilts of the test object by fixed angles α around the y-axis have only longitudinal parallax of points, and measuring their differences allows obtaining the heights of the points on the object's microsurface.

Due to the flexibility of this method, stereo pairs obtained, for example, with a scanning electron microscope, optical microscope, or digital camera can be analyzed.

Summary of the main material and scientific results. For the study, samples of a structural alloy were selected – a medium-strength alloy of the Al-Cu-Mg system (3.1325 – EN AW-2017A), which, due to its special properties, is used in various technical fields, in particular in aircraft construction for the manufacture of parts subjected to significant loads.

The structural alloy of the Al-Cu-Mg system is known for its high strength, as copper, magnesium, and manganese significantly increase the strength of aluminum alloys, so that the strengthening process of this system can be controlled mainly by the magnesium content [8]. These alloys are characterized by high mechanical and fatigue strengths, and have increased fracture toughness and crack resistance.

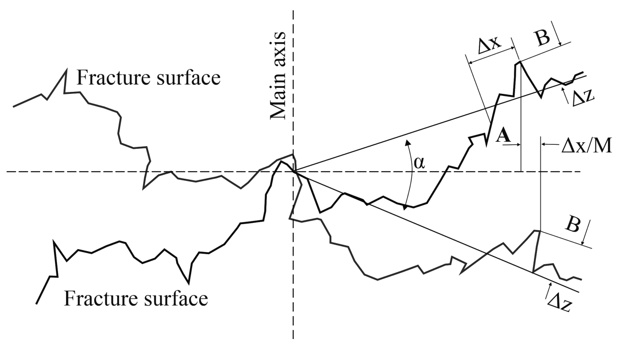

Fig. 3. Determination of parallax Δx from a pair of stereo images, where Δx is the parallax determined in the image; the ratio $\Delta x/M$ is the parallax that occurs on the fracture surface

In this work, dispersion hardening was studied on the example of five test samples of Al-Cu-Mg alloy: four samples with heat treatment and one sample without heat treatment. The strength values of the pressed profiles and the content of alloying elements of the experimental Al-Cu-Mg alloys are given in Table 2.

Heat treatment modes – T4: hardening combined with natural aging according to [19].

Al-Cu-Mg alloys are among the high-strength alloys that undergo dispersion aging. Dispersion hardening of Al-Cu-Mg alloys, unlike other aluminum alloys, occurs at room temperature. When the material is subjected to natural aging, its alloying elements precipitate. Accordingly, the following heat treatment regime is required: mild (recrystallization) annealing and subsequent natural aging. With this heat treatment regime, the strength increases many times, and the Al-Cu-Mg alloy can fully reveal its potential.

The first type of annealing helps to eliminate deviations in the structure of alloys from the equilibrium state. At the 1st stage, samples of Al-Cu-Mg alloys are heated to a soft annealing temperature of 480 °C for 4 hours, after which the temperature is reduced to 230 °C and cooled for 8 hours.

At the *2nd* stage, the samples are heated at 230 °C for 3 hours, after which they undergo a hardening process (natural aging) at room temperature for 5–8 days. The hardness value after soft annealing is 54.6 HV10.

After soft annealing, the samples are subjected to solid solution annealing at 530 °C for 1.5 hours, after which they are soaked and cooled to room temperature. After annealing, the hardness increases from 54.6 Hv10 to 80 Hv30.

The mechanical properties of the experimental alloys after heat treatment were evaluated based on the results of dynamic tensile and impact strength tests.

Tensile tests were performed on standard specimens in accordance with DSTU EN 10002-1:2006.

As a result of the tensile test, a deformation diagram was obtained (Fig. 4), which reflects the relationship between the load and elongation of the test alloy samples and its main characteristics (Table 3).

Impact toughness tests for the sample with a V-shaped notch were performed on a Wolpert pendulum tester using the Charpy method with a load of 150 J at room temperature (according to DSTU ISO 148-1:2022).

Table 1

The dependence of vertical resolution on the angle of inclination

Tilt angle, 2α, °	Vertical resolution, μm
5	574
10	288
15	193
20	146

Table 2

The strength value of extruded profiles and the content of alloying elements of Al-Cu-Mg alloy prototypes

Series/ Chem. name	Content of alloying elements,%	Tensile strength Rm, N/mm²	Yield strength $R_{p0.2}$, N/mm²	δ, %	Brinell's hardness HB
EN AW 20217A AlCu4MgSi (A)	Si 0.2–0.8 Cu 3.5–4.5 Mn 0.4–1.0 Mg 0.4–1.0	350–390	240–250	4–12	101–110

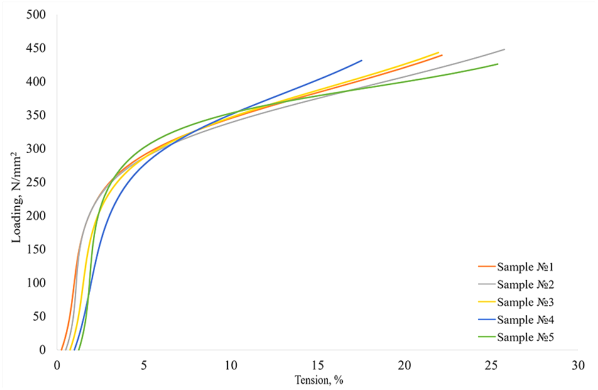

Fig. 4. Deformation diagram for samples No. 1–5

The results of the impact toughness tests of the experimental Al-Cu-Mg alloy are given in Table 4.

The results of dynamic tests to determine the impact strength show almost identical mechanical properties. It can be stated that the heat treatment of Al-Cu-Mg (samples No. 1–4 – natural aging) does not provide significant advantages compared to the sample of the experimental Al-Cu-Mg alloy without heat treatment (sample No. 5).

At the next stage, after determining the mechanical properties of the experimental alloys of the Al-Cu-Mg system, the microsurfaces of fractures were studied.

Microfractographic studies of the fracture surfaces of the experimental alloys were carried out on a scanning electron microscope REM LEO 14 XX(VP) and an energy dispersive analyzer – EDX at OWL University of Applied Sciences and Arts (Germany).

Establishing fracture mechanisms is an important and complex problem, especially when such processes are studied at the micro level. The variety of tasks that can be set when studying the microstructure of fractures excludes the possibility of a single approach and a single methodology for their study, so the research method should be chosen taking into account the task and the nature of the object under study.

Table 3

Results of tensile tests for samples of Al-Cu-Mg test alloys, samples No.1–4 (natural aging) and sample No. 5 (without heat treatment)

No.	HV30	EMod H/mm²	$R_{p0.2}$ H/mm²	Rm H/mm²	R_B H/mm²	δ, %	Ψ, %
1	124	55,080	272.9	439.2	437.3	22.16	18.52
2	125	61,613	274.4	447.8	429.8	25.75	31.07
3	127	67,026	276.3	443.0	441.9	21.95	20.73
4	126	49,900	269.2	431.2	429.7	17.53	16.51
5	123	71,709	301.5	425.8	394.4	25.36	33.66

EMod – modulus of elasticity

Table 4

Impact Test Results of Al-Cu-Mg Experimental Alloy Test Results (EN AW-2017, 3.1325)

No.	Hardness, HV30	Impact strength with notch, J/cm²
Samples No. 1–4 Natural aging		
1	133	16
2	135	15.5
3	133	16
4	133	16.5
Sample No. 5 without heat treatment		
5	134	12

Using microstructural analysis of SEM images in combination with EDX analysis, it is possible to determine the type of fracture: transcrystalline or intercrystalline [10] and to analyze the chemical composition of the solid solution and the precipitates present in it.

The fracture surface of the Al-Cu-Mg prototype (natural aging) after the impact strength test is deformed with an inclined sliding plane along the edge and a crater. The fracture surface shows a transcrystalline honeycomb fracture (fracture occurs along the grain body). There are inclusions (precipitates) at the bottom of the cells.

The fracture surface of the Al-Cu-Mg sample is matte, and there is a narrowing of the sample that preceded the fracture.

Fig. 5 clearly shows an intercrystalline brittle fracture with a fine honeycomb structure. The cellular structure runs along the grain boundaries.

Dispersion hardening is hardening due to the release of a large number of secondary (fine) phase particles from a supersaturated solid solution. Dispersion hardening depends on the size of the precipitates, the distance between them, and their chemical composition. Identification of precipitates by SEM makes it possible to determine their physical and chemical properties in different states. After cold quenching of the test samples, only coherent deposition occurs. The size of inclusions (precipitates) is 2.5–3 microns.

The SEM images of the fracture surfaces mainly show a honeycomb structure, which is typical for ductile metal materials. The honeycomb structure consists of many different substructures, some of which penetrate each other, vary in length and depth. Only a few cells are perfectly shaped, while most are highly irregular and fragmented.

Based on the results of stereometric processing of the SEM images, 429 irregular grid nodes were identified, in which three-dimensional coordinates were determined in the pixel image coordinate system. The three-dimensional interpretation of the surface microrelief was carried out by the method of minimum curvature (Fig. 6).

Based on the obtained three-dimensional surface, data was extracted to build a map of peaks and troughs (Fig. 7).

This type of map is useful for modeling the movement of water over land masses and landscapes characterized by caves, sinkholes, fissures, and underground streams. Boundaries are drawn around peaks (red areas) and troughs (blue areas) to create unique areas for statistical analysis. Areas of anomalies (purple areas) that stand out sharply within the trough regions are identified by comparing the raster image and the digital elevation model as sediments.

Aluminum-copper alloys of the Al-Cu-Mg series gain strength during aging at room temperature due to the formation of precipitates containing copper. The size, spatial distri-

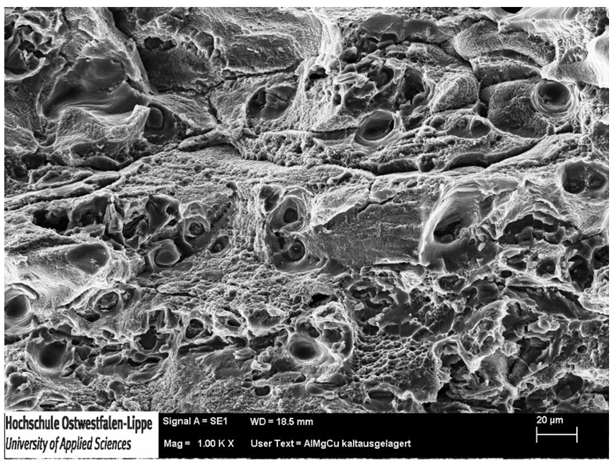

Fig. 5. SEM image of the fracture surface of the sample Al-Cu-Mg (natural aging) after tensile testing

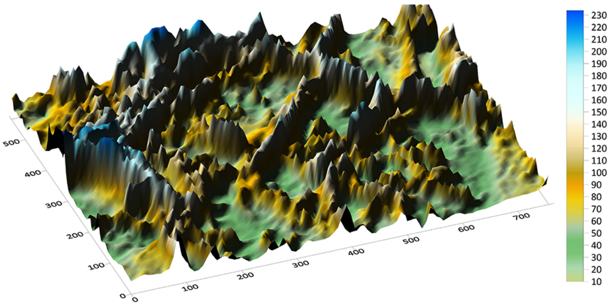

Fig. 6. A digital model of the microrelief of a fracture surface fragment showing inclusions (precipitates)

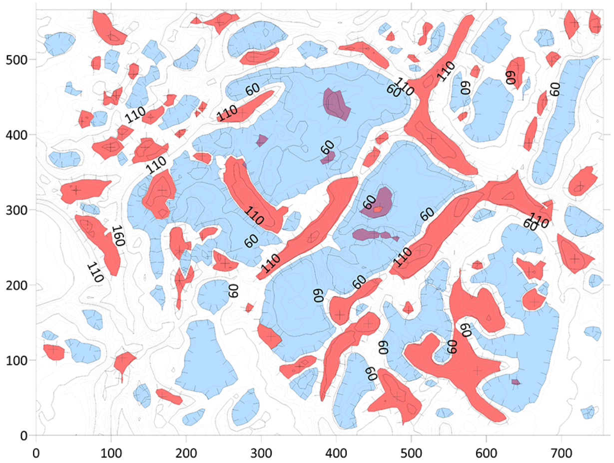

Fig. 7. Maps of peaks and troughs of the fracture surface fragment

bution, and crystal structure of these precipitates have a significant impact on the mechanical properties of these alloys. In order to analyze the process of precipitation formation, to identify the chemical composition of the precipitation particles and their influence on strength, we used the method of energy dispersive EDX analysis.

Areas with different chemical compositions can be identified by scattered electrons, and quantitative chemical analysis can be performed using EDX. Each measured area is recorded with its coordinates so that it can be found again at any time for further research. The chemical composition of the inclusions – sediments is presented in Table 5.

The results of EDX analysis and the mass percentage of elements of the sample subjected to natural aging are presented respectively in Fig. 8 and in Table 6 respectively.

Similar results for the sample without heat treatment are shown in Fig. 9 and Table 7.

Conclusions. The photogrammetric assessment of samples in the micro range has numerous advantages. The results presented in this work demonstrate the flexibility and accuracy potential of photogrammetric measurement methods in the micro range.

Due to the lack of control points in the micro range, further development of SEM calibration and self-calibration methods is required, as well as testing of different acquisition methods and the number of images. In the case of photogrammetric evaluation in the micro range, it must be taken into account that the samples under measurement have very different shapes.

Table 5

Determined composition: in % wt., the rest is aluminum

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn
Al-Cu-Mg	0.20–0.8	0.70	3.5–4.5	0.40–1.0	0.4–1.0	0.10	0.25

Al_2Cu weight ratio: 54/63.5

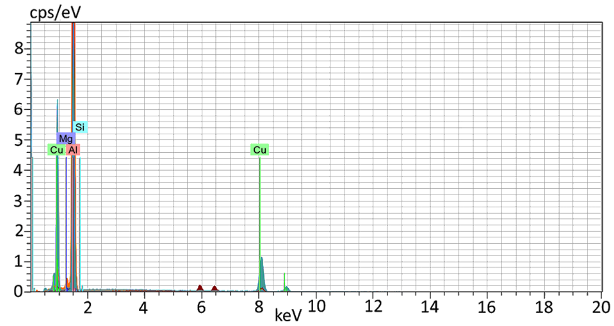

Fig. 8. Results of EDX analysis of Al-Cu-Mg alloy sample (natural aging)

Table 6

Distribution of % wt. elements of experimental sites (natural aging)

Research site	Mg	Al	Si	Cu
Site 1	0.58	53.13	0.18	46.11
Site 2	0.94	94.80	0.66	3.60
Site 3	0.98	94.41	0.44	4.17

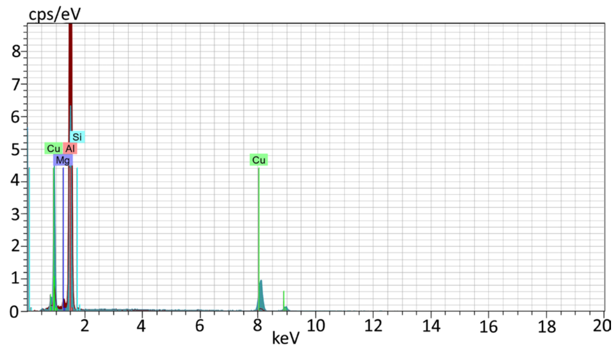

Fig. 9. Results of EDX analysis of Al-Cu-Mg alloy sample (without heat treatment)

Table 7

Distribution of % wt. elements of experimental sites (without heat treatment)

Research site	Mg	Al	Si	Cu
Site 1	0.46	54.03	0.34	45.16
Site 2	1.08	94.24	0.73	3.95

In addition to the study on methodological and accuracy aspects, attention was focused primarily on the practical application and integration of individual algorithms and procedural steps into a continuous process of fracture surface assessment. In the photogrammetric processing of SEM images, the physical and technical conditions of image recording also play an important role. By calibrating the goniometer table, the time-consuming process of orienting a series of images can be avoided

The research demonstrates the flexibility and accuracy of photogrammetric measurement methods in the micro range. These methods do not depend on the scale of recording systems and can be used for different types of scanning electron microscopes, which opens up wide possibilities for their application. Further research is needed to determine the method for determining sediments and inclusions through the study on digital microrelief models.

Comparing the results of mechanical and metallographic studies, it can be concluded that the desired properties of the samples are achieved after dispersion hardening. Thus, it is confirmed that the samples are processed under optimal hardening conditions. After studying the dispersion hardening of the Al-Cu-Mg aluminum alloy, it can be predicted that, theoretically, the strength can be further increased by artificial aging due to the appearance of partially coherent allocation.

Further research on dispersion hardening during artificial aging is advisable to be able to determine the highest strength.

References.

1. Bhat, B. N. (2018). *Aerospace materials and Applications*. American Institute of Aeronautics and Astronautics, Inc.

2. Chen, J., Ling, K., Deng, P., Mo, W., Tang, C., Ouyang, Z., Luo, B., & Bai, Z. (2023). Effect of Mg content on microstructure, mechanical properties and intergranular corrosion properties of Al-Cu-Mg-Ag alloys. *Materials Today Communications*, *34*, 105363. https://doi.org/10.1016/j.mtcomm.2023.105363.

3. *DIN EN 573-3:2019+A1:2022 – Aluminium and aluminium alloys – Chemical composition and form of wrought products – Part 3: Chemical composition and form of products* (2022).

4. Hemmleb, M. (2002). *Photogrammetrische Auswertung elektronenmikroskopischer Bilddaten*. https://doi.org/10.14279/depositonce-321.

5. Ivanov, R., Deschamps, A., & De Geuser, F. (2018a). Clustering kinetics during natural ageing of Al-Cu based alloys with (Mg, Li) additions. *Acta Materialia*, *157*, 186-195. https://doi.org/10.1016/j.actamat.2018.07.035.

6. Ivanov, R., Deschamps, A., & De Geuser, F. (2018b). High throughput evaluation of the effect of Mg concentration on natural ageing of Al-Cu-Li-(Mg) alloys. *Scripta Materialia*, *150*, 156-159. https://doi.org/10.1016/j.scriptamat.2018.03.024.

7. Klobes, B., Maier, K., & Staab, T. E. M. (2011). Natural ageing of Al-Cu-Mg revisited from a local perspective. *Materials Science and Engineering: A*, *528*(7), 3253-3260. https://doi.org/10.1016/j.msea.2011.01.002.

8. Kolednik, O. (1981). Ein Beitrag zur Stereophotogrammetrie am Rasterelektronenmikroskop. *Praktische Metallographie*, *18*, 562-573.

9. Kovarik, L., & Mills, M. J. (2012). Ab initio analysis of Guinier–Preston–Bagaryatsky zone nucleation in Al–Cu–Mg alloys. *Acta Materialia*, *60*(9), 3861-3872. https://doi.org/10.1016/j.actamat.2012.03.044.

10. Luhmann, T. (2010). *Nahbereichsphotogrammetrie – Grundlagen, Methoden, Anwendungen*.

11. *Metals handbook. Volume 12: Fractography* (n.d.). Retrieved from https://www.osti.gov/biblio/6512607.

12. Motro, P. F. K., Kursoglu, P., & Kazazoglu, E. (2012). Effects of different surface treatments on stainability of ceramics. *The Journal of Prosthetic Dentistry*, *108*(4), 231-237. https://doi.org/10.1016/S0022-3913(12)60168-1.

13. Patel, V., Li, W., Vairis, A., & Badheka, V. (2019). Recent development in friction stir processing as a solid-state grain refinement technique: microstructural evolution and property enhancement. *Critical Reviews in Solid State and Materials Sciences*, *44*(5), 378-426.

14. Piazzesi, R., Berrilli, F., Del Moro, D., & Egidi, A. (2012). Algorithm for real time flare detection. *Memorie della Societa Astronomica Italiana Supplementi*, *19*, 109.

15. Schmid, M., Liebel, A., Moldovan, G., Lackner, R., Steigenhöfer, D., Niculae, A., & Soltau, H. (2018). New Possibilities for State-of-the-Art Electron Microscopy with Fast Backscattered Electron Detectors. *Microscopy and Microanalysis*, *24*(S1), 650-651.

16. Solís Moreno, C., Sanz-Moliner, J. D., Pascual La Rocca, A., Nart, J., & Santos Alemany, A. (2013). In vitro evaluation of the root surface microtopography following the use of two polishing systems by Confocal Microscopy (CFM) and Scanning Electron Microscope (SEM). *Oral Health and Dental Management*, *12*(4), 243-247.

17. Uhl, A., Melnyk, Y., Melnyk, O., Boyarska, I., & Melnychuk, M. (2020). Application of Microphotogrammetric and Material Science Techniques in the Study of Materials on the Example of Alloy AlZnMgCu. In B V. Ivanov, J. Trojanowska, J. Machado, O. Liaposhchenko, J. Zajac, I. Pavlenko, M. Edl, & D. Perakovic (Eds.). *Advances in Design, Simulation and Manufacturing II*, (pp 477-486). Springer International Publishing.

18. Uhl, A. V., Melnyk, O. V., Melnyk, Y. A., & Ilyin, L. V. (2021). Microphotogrammetric approach in the study of alsimg alloys. *Metallofizika i Noveishie Tekhnologii*, *43*(2). https://doi.org/10.15407/mfint.43.02.0255.

19. Yang, Z., Erdle, I., Liu, C., & Banhart, J. (2022). Clustering and precipitation in Al-Mg-Si alloys during linear heating. *Journal of Materials Science & Technology*, *120*, 78-88. https://doi.org/10.1016/j.jmst.2021.11.062.

Застосування стереомікрофотограмметричного методу для комплексного дослідження сплавів системи Al-Cu-Mg

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Мета. Поєднання стереофотограмметричного методу обробки зображень поверхні руйнування на мікрорівні із результатами серії механічних і металофрактографічних досліджень із прецизійними методами растрової електронної мікроскопії (РЕМ) та енергодисперсійного аналізу (EDX) для визначення особливостей і загальних закономірностей руйнування дослідних зразків сплаву системи Al-Cu-Mg.

Методика. У роботі експериментально визначені механічні властивості зразків дослідних сплавів системи Al-Cu-Mg після м'якого (рекристалізаційного) відпалу й подальшого природного старіння та зразку без термічної обробки. На наступному етапі проведені РЕМ-стереомікрофрактографічні дослідження зламів і їх тривимірна реконструкція за отриманими стереозображеннями. Енергодисперсійні дослідження проведені для різного роду ділянок зразків для встановлення розподілу масових відсотків елементів дослідних ділянок. У роботі застосована комплексна методика експериментальних досліджень сплавів системи Al-Cu-Mg з метою отримання якісної й кількісної інформації про мікроструктуру зламів, що складалась з наступних етапів: визначення механічних властивостей зразків дослідних сплавів традиційними методами макро- й мікроаналізу; дослідження стереопар мікроструктури зламів стереофотограмметричним методом; ідентифікація хімічного складу та структури частинок осаджень матриці методом енергодисперсійної рентгенівської спектроскопії (EDX-аналізу).

Результати. Із проведених експериментів встановлено, що зі збільшенням часу тривалості природнього старіння твердість повільно зростає й досягає максимального показника твердості 127 Hv30 після 97 годин, зниження якого згодом не відбувається. Після природнього загартування середня межа міцності при зламі зростає до Rm 440,3 при відносному видовженні 21,8 %. Механічні випробування показали, що міцність на розрив зростає зі збільшенням значення твердості та, навпаки, в'язкість зменшується. Енергія, що необхідна для руйнування зразка, становить 16 Дж, після чого відбувається транскристалічний стільниковий злам. Осади мають діаметр приблизно 2,5–3 мкм.

Наукова новизна. Порівнюючи результати механічних і металографічних досліджень, можна стверджувати, що бажані властивості зразків Al-Cu-Mg проявляються після дисперсійного зміцнення, що підтверджує оптимальні умови затвердіння. Результати фотограмметричної оцінки зразків у мікродіапазоні, представлені в роботі, демонструють гнучкість і потенціал точності фотограмметричних методів вимірювання й подальшої їх обробки, інтерпретації та інтеграції з EDX-аналізом для вибору оптимальних ділянок дослідження.

Практична значимість. У роботі апробовано комплексний підхід до аналізу матеріалів із застосуванням РЕМ-стереомікрофотограмметричного методу, механічних і металографічних досліджень, а також енергодисперсійного аналізу.

Ключові слова: *сплав Al-Cu-Mg, РЕМ-стереомікрофотограмметрія, механчні дослідження, металографічні дослідження, EDX-аналіз*

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