Fatigue cracking of aluminium alloy AlZn6Mg0.8Zr subjected to thermomechanical treatment

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ABSTRACT. The paper presents the results of experimental test of the fatigue of aluminium alloy type AlZn6Mg0,8Zr exposed to various low temperature thermomechanical treatment. Basquin's characteristics of fatigue have been determined in mechanical test on smooth specimens at a simple state of loading in conditions of alternating bending. The tests were carried out on a fatigue test stand constructed by the authors – MZGS 100. The development of fatigue cracking has been described based on metallographic and fractographic investigations of the fractured samples making use of a scanning electron microscope (SEM). The results of qualitative microfractography of the tested samples in the low-cycle temporal range of fatigue strength revealed fractures of the transcrystalline quasi-cleavage type. It has also been found that local effects of intercrystalline brittle cracking of this type do occur.

KEYWORDS. Aluminium alloy; Fatigue tests; Thermomechanical treatment; Fatigue cracking; SEM.

INTRODUCTION

Aluminium alloys as well as their technology constitute an important position in the design and construction of light but highly resistant structures in many branches of industry, both civilian industry and that producing military equipment. A reduction of the mass of vehicles and the consumption of fuel, a higher carrying capacity, less expensive and safest structures, and also ecological aspects are actually the fundamental criteria in the choice of adequate material, not only in the automotive and aircraft industry, but also in ship-building and the production of machines structures of transport. This requires a constant development in the technology and improvement of the properties of aluminium alloys, resulting in a higher effectiveness in various applications. Thanks to their high relative strength (R_m/ρ) and resistance to impacts, their inurement to brittleness, non-magnetic (paramagnetic material) and good resistance to corrosion in a marine environment, these alloys are applied, among others, in the shipbuilding, particularly of a fast non-displacing vessels, such as landing crafts, rocket cutters, submarines, hydrofoil boats and other vessels carrying considerable dynamic and fatiguing loads, as well as touristic and sport units.
An essential problem of the technology of aluminium alloys is not only the formation of their mechanical properties, but also their formation by means of casting, plastic deformation, freeform fabrication or machining [1]. One of the effective

ways of achieving a good resistance and plasticity is their thermomechanical treatment [2]. Their mechanical properties and resistance to cracking are considerably attained by the jointly acting mechanisms of strain hardening and precipitation. A crucial feature affecting the widely understood properties of aluminium alloys is their microstructure, mainly the size and morphology of the particles of the intermetallic phases arising due to alloying additions, usually soluble phases remaining in a thermodynamic equilibrium with the matrix.

The microstructure of aluminium alloys is also an essential factor of their fatigue strength. Their resistance to cracking due to fatigue depends both on the mechanism of the nucleation of cracking and the aptitude to dissemination in the material. The microstructural factors restricting an easy nucleation of cracking due to fatigue are mainly hardening precipitations with a considerable dispersion, not sheared by mobile dislocations and the reduction of the relative volume of big particles of intermetallic phases, as well as the formation of fine recrystallized grains in the structure of the aluminium alloys. The destruction caused by fatigue often displays the character of brittle cracking, even in ductile alloys, due to accompanying slight plastic deformation. The fatigue of the material caused by a sustained development of cracking due to cyclically changing loads is, therefore, a dangerous form of degradation of many load-bearing structures and mobile elements of machines. This is why further investigations are still required concerning this problem. Thus, the aim of the undertaken experimental investigations was to determine the influence of differentiated conditions of loading in the course of low- and high-cyclical oscillatory bending on the fatigue strength and resistance to fatigue of cracking of aluminium alloys subjected to plastic working of the AlZn6Mg0.8Zr type of the 7000 series after their low-temperature thermomechanical treatment [3, 4].

EXPERIMENTAL PROCEDURE

The investigated material was an industrial aluminium alloy of the Al-Zn-Mg type belonging to the grade 7003 according to PN-EN [5] in the shape of a sheet with the dimension 400x200x20 mm. The chemical composition of this alloy is to be seen in Tab. 1, and its mechanical properties in the delivery state and after the thermomechanical treatment in Tab. 2. Al-Zn-Mg alloys of the 7000 series display the highest potential of strength among the alloys subjected to hardening precipitation. Some of them contain copper in order to improve their resistance to stress corrosion. The overall content of Z+Mg < 6% warrants a satisfactory resistance to cracking.

Denotation of the alloy and the type of analysis	Chemical composition (mass %)								
	Zn	Mg	Mn	Fe	Cr	Si	Zr	Cu	Al
EN AW-7003 EN AW-Al Zn6Mg0.8Zr	5.0 6.5	0.5 1.0	0.3	0.35	0.2	0.3	0.05 0.25	0.2	bal.
Analysis of smelting	6.13	0.74	0.29	0.20	0.17	0.12	0.08	0.04	bal.

Table 1: Chemical composition of investigated alloy.

State of materials \ Mechanical properties	$\overline{R_{p0.2}}$ [MPa]	$\overline{R_m}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]
Delivered	347.0	400.4	14.1	35.5
Low-temperature thermomechanical treatment	255.8	321.2	10.2	49.5

Table 2: Mechanical properties of investigated alloy.

The investigated alloy was subjected to a low-temperature thermomechanical treatment as shown in Fig. 1:

- preheated up to 500°C and soaked for one hour,
- cooled down in water,

- cold-rolled with a degree of deformation of 10%.
- ageing of the material for 12 hours at a temperature of 150°C, then cooled down in the open air.

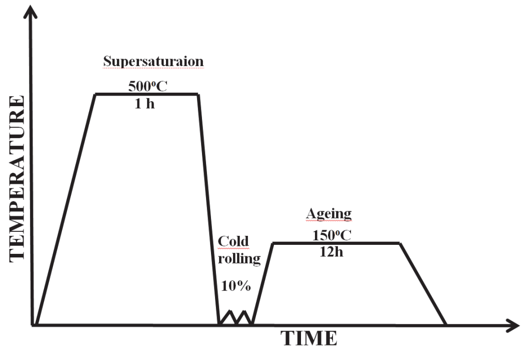
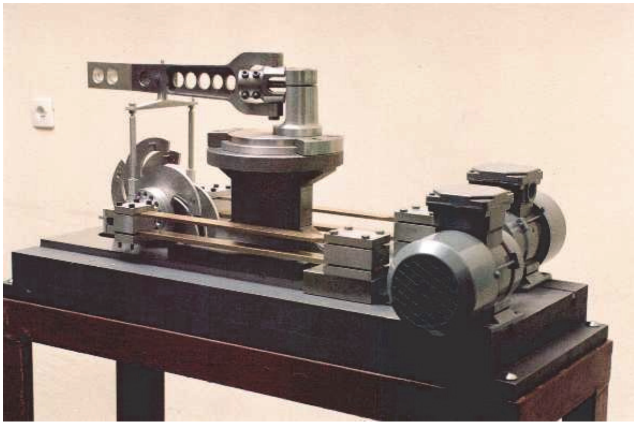
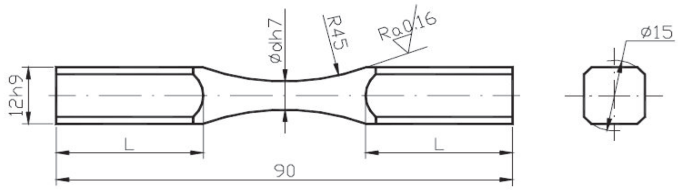


Figure 1: Scheme of low-temperature thermomechanical treatment of AlZn6Mg0.8Zr alloy.

The fatigue strength was tested on a test-stand MZGS-100 [6] (Fig. 2a) applying smooth standard samples (Fig. 2b) and a simple state of loading of the type oscillatory bending. Besides the possibility of cycling bending at a constant value of the bending moment and fatigue torsion, the test stand permits also provide the sample with complex state of bending stresses connected with its torsion. Basing on the performed fatigue tests the fatigue characteristics of Basquin could be determined in the system: amplitude of stresses (σ_a) – number of cycle up to the fatigue (N_f).





a) b)

Figure 2: Test stand MZGS-100 (a) and specimen of fatigue strength test (b).

Metallographic tests were carried out on microsections of longitudinal samples stretched statically and tested concerning their fatigue. The preparation of the microsections comprised standard operations of submerging the samples in chemohardened resign, grinding and mechanical polishing on s Struers Labo Pol – 21 machine, as well as etching in a 2% solution of hydrofluoric acid in water. The structure was observed making use of the light microscope OLYMPUS GX71F with a magnifying power of 200 to 1000 times.

For fractographic investigations fractures of samples after the decohesion in fatigue bending tests were used. For this purpose an electron scanning microscope (SEM) of the ZEISS SUPRA 25 type was applied with an electron part GEMINI with a voltage of 20 kV and a magnifying power of 140 to 1500 times. The chemical composition of the precipitations was analyzed on the fractures applying the method of X-ray microanalysis and probe EDAX.

RESULTS

The results of mechanical fatigue tests of samples of the AlZn6Mg0.8Zr alloy have been gathered in the diagram (Fig. 3). It has been found that the standard characteristics of fatigue according to Basquin, determined in the range fatigue strength in time is typically for metallic materials and can be described statistically by a straight line of regression in the equation y = -14x + 252. The maximum bending moment and the amplitude of stresses σ_a of about 190 MPa was recorded at the number of cycles N_f about $6 \cdot 10^4$, whereas minimum amplitude of stresses σ_a of about 160 MPa was recorded with the number of cycles N_f about $2 \cdot 10^6$. The samples tested in the fatigue test are subjected to varying loads bending of a cyclic character. The stresses and deformations resulting from these loads lead to a fatigue of the material and are the main reason of the initiation of its cracking. It has also be found that the analyzed cracking caused by fatigue is of a stochastic character, unforeseeable, and therefore requiring a constant development of investigations concerning this branch of knowledge, both from the viewpoint of cognition and of practical use. Basing on the determined characteristics of fatigue (σ_a – N_f) we can determine the durability to fatigue of the investigated alloy. It is inevitable to estimate the fatigue life of the tested samples in order to prolong the possibility of exploitation and reliability and safety of the respective elements of the structure and mobile parts of machines consisting of the Al-Zn-Mg alloy.

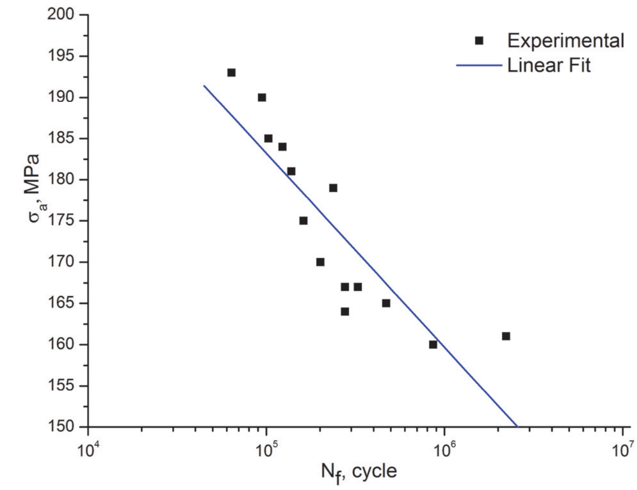


Figure 3: Basquin's fatigue characteristics concerning the AlZn6Mg0.8Zr alloy loaded due to cyclic bending.

Metallographic observations revealed that in result of employing the variant of thermomechanical treatment, the transverse samples (LT) of the investigated alloy display a microstructure consisting of deformed grains of the matrix of the solution-α and numerous particles of intermetallic phases, differing in their size by about 3÷15 μm², distributed in bands in the direction of crawling of the material during its plastic treatment, or occurring in local clusters in the grains of at their boundaries (Figs. 4÷6). An X-ray microanalysis (EDX) has shown that these may be, among others, larger phase particles of the type Mg_2Si, $Al_6(FeMn)$ or $Al_2(FeMn)_3Si$, insoluble at the temperature of supersaturation (Fig. 6). These particles, probably of a primary character, do not contribute to an increase of the tensile strength, but may effect a decrease of the resistance to cracking and affect evidently the fatigue strength.

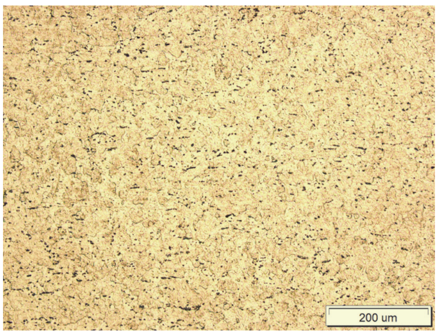


Figure 4: Precipitation of the particles of intermetallic phases in the matrix of the solution-α of the AlZn6Mg0.8Zr alloy

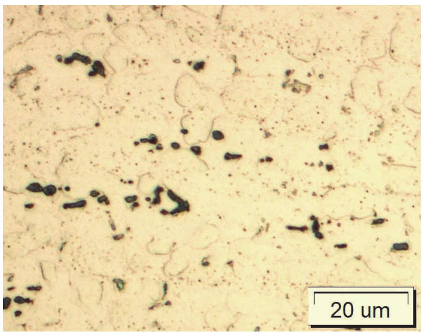


Figure 5: Particles of intermetallic phases distributed in bands and particles occurring in clusters

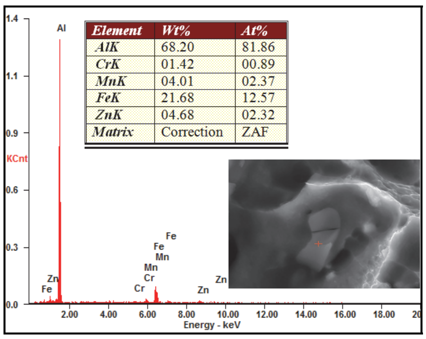


Figure 6: X-ray microanalysis of the chemical composition of precipitation at the bottom of the crater

The results of qualitative microfractography of the tested samples of the AlZn6Mg0.8Zr alloy after the fatigue test have been presented in the microphotographs in Figs. 7 to 12. The fracture obtained in the range of low-cycling and restricted fatigue strength at the maximum value of the amplitude of stresses (σ_a) amounting to 190 MPa is of the transcrystalline quasi-cleavage type (Fig. 7), demonstrating mainly flat and smooth surfaces of jogs in the planes of cleavages, practically without any traces of plastic deformation of the surface. Evident is also the local occurrence initiation of brittle intercrystalline cracking (Fig. 8). The observed details of fractures caused by fatigue suggest in this case a interlocking mechanisms of fracture, which is characteristic for processes of plastic deformation of cold-rolled metals and alloys. A somewhat different microfractography was detected in samples of the investigated Al-Zn-Mg alloy subjected to varying bending loads in the case of the minimum value of the amplitude of stresses (σ_a) amounting to about 160 MPa in the boundary zone of fatigue. In the surface zone of the tested samples symmetric local points of the fracture have been noticed (Fig. 9) with smooth primary jogs in the character of transcrystalline cleavage, planes and numerous tongue-steps. Evident are also local overstrains of the material and intercrystalline cracks (Fig. 10). A detailed microfractographic analysis of the tested samples of the alloy with the FCC lattice permitted to see that the observed transcrystalline quasi-cleavage fracture (Fig. 11) indicates distinctly a larger share of plastic deformation on the surface of the steps as well as traces of such a deformation on potentially stochastic surfaces of cleavage (Fig. 12). The grain boundaries of the Al-Zn-Mg alloy with a differing orientation probably impede the propagation of cleavage cracking due to various systems of steps, and also by the absorption of energy in the course of cracking. Thus, in the investigated conditions of fatigue the degree of brittleness can be decreased and the plasticity of the alloy improved.

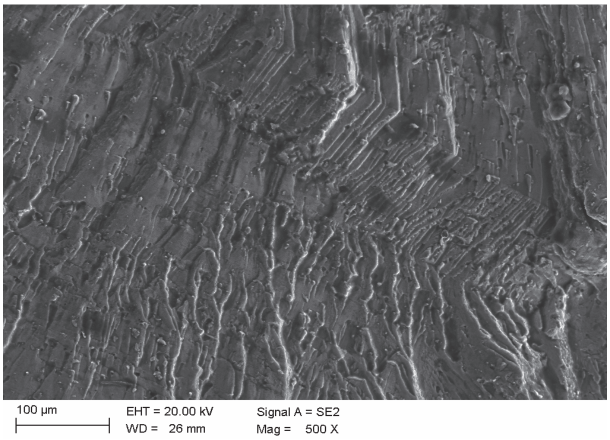


Figure 7: Transcrystalline quasi-cleavage fracture with flat and smooth surfaces of the AlZn6Mg0.8Zr alloy

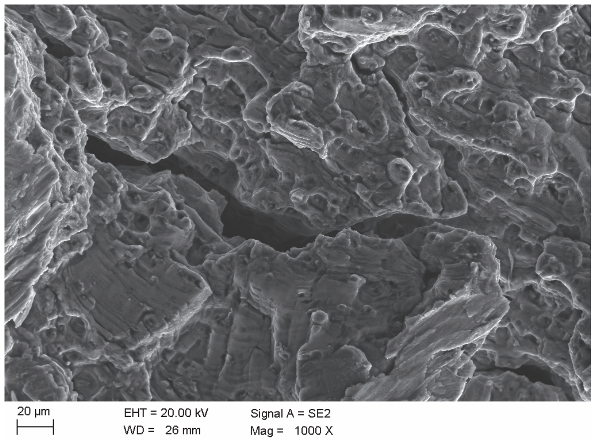


Figure 8: Transcrystalline cleavage fracture with a local initiation of brittle cracking of the intercrystalline type of the investigated alloy

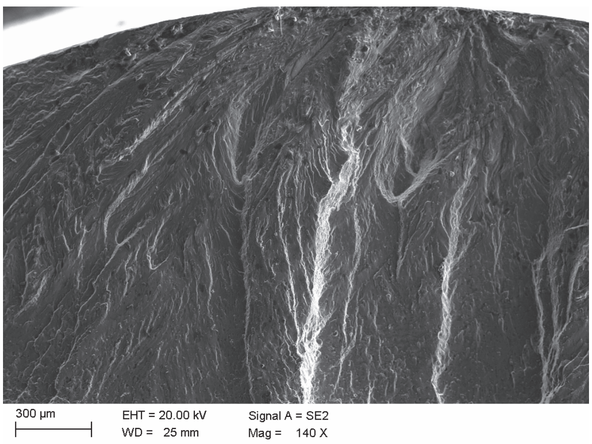


Figure 9: Symmetric focal points of a fracture in the surface zone with primary jogs of the investigated alloy.

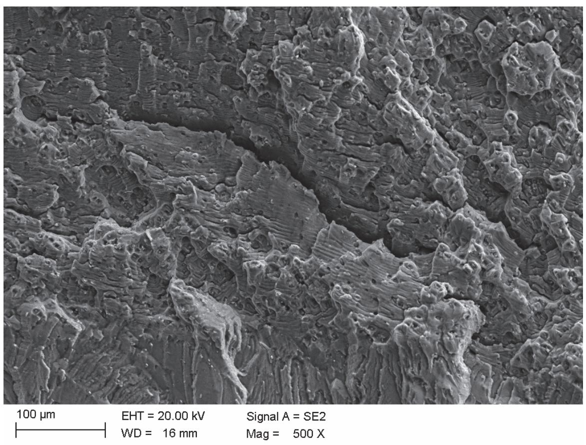


Figure 10: Temporary zone of a fracture, local cracking of the intercrystalline character of the AlZn6Mg0.8Zr alloy.

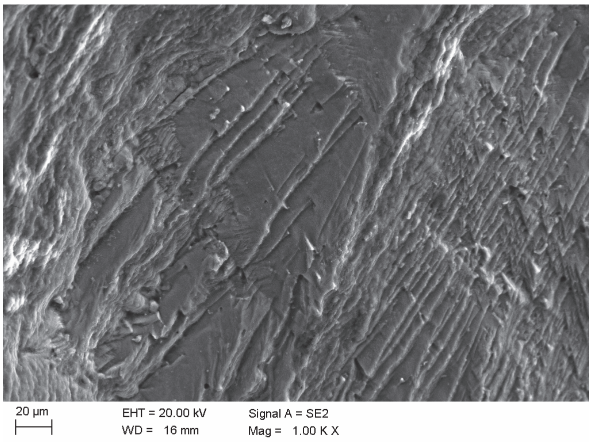


Figure 11: Transcrystalline quasi-cleavage fracture with an increases share of plastic deformation on the surface of jogs of the investigated alloy.

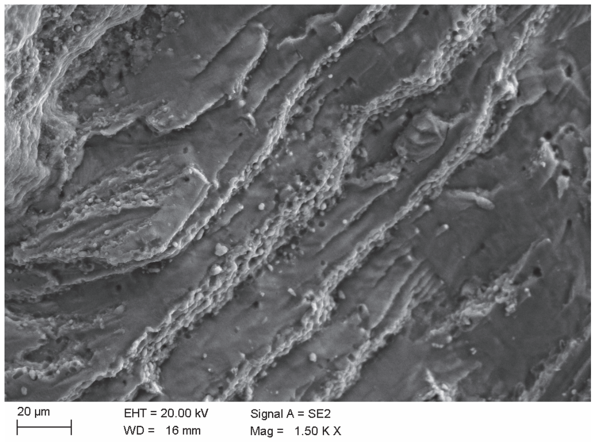


Figure 12: Trace of plastic deformation on cleavage surface of AlZn6Mg0.8Zr alloy.

DISCUSSION

The formation of new kinds of aluminium alloys with more favorable mechanical properties requires a penetrating scientific analysis actually aided by numerical methods, concerning both the chemical composition and technical processes. It has been found that the crucial feature affecting the widely understood properties of aluminium alloys is their microstructure, particularly their dimensions and shape of the grains, the dislocation structure, the size and morphology and distribution of the particles of the intercrystalline phases, mainly of phases with a large dispersion. Every one of these factors of the microstructure is essentially affected by the applied technological process of aluminium alloys assigned for plastic working. Cold rolling after supersaturation of the aluminium alloy belonging to the 7003 series permits to attain a higher strength thanks to the increased density of dislocations and higher share of nucleation of hardening phases, ensuring the formation of particles with a larger dispersion and restricting considerably the formation of zones without precipitations along the grain boundaries.

The role of particles with a larger dispersion (submicroscopic dispersion) in the process of cracking of the aluminium alloy is, however, more complex. Their influence on the resistance of the alloys is both positive and negative. They affect positively the restriction of the growth of the grains. Small grains promote transcrystalline cracking, absorbing much energy. On such particles nucleate, however, also microvoids which may lead to an increased share of platforms between other voids appearing on big precipitations. This also affects considerably the process of destruction due to fatigue, resulting from the nucleation and increased cracking on the surface of elements exposed to varying loads. In the layer adjacent to the surface the stresses concentrate due, among others, to the presence of big particles of precipitations, bands of sliding, microintrusions or extrusions, as well as to zones deprived of precipitations along the grain boundaries adhesing to the surface.

The resistance to cracking depends mainly on the inclination of the alloy to nucleation and the propagation of cracking. Thus, the microstructural factors restricting an easy nucleation of cracking caused by fatigue are undoubtedly precipitations of the intermetallic phases, hardening the aluminium alloys susceptible to shearing by dislocation or recrystallized grains retaining the minimum relative volume of big particles of primary precipitations. The rate of the increase of cracking due to fatigue depends also on the character of sliding. Sliding in big grains and the presence of precipitations crossed by dislocations promote the development of cracking caused by fatigue [7]. Plastic deformation in the course of thermomechanical treatment increases the density of dislocations, which again restricts the formation of broad bands of sliding during the deformation resulting from fatigue. Paradoxically, also the presence of numerous of intermetallic precipitations phases with large dimensions can prevent a localization of deformations in the slide bands, thus increasing the fatigue strength.

The analysis of the results of many fatigue tests of aluminium alloys leads to the conclusion that the optimal mechanical properties of these alloys may condition the bimodal distribution of the size of precipitations of hardening phases, i.e. dispersive precipitations (from 1 nm to about 10 nm), increasing the yield point and tensile strength of the alloys and of particles with a diameter of 0.01 μm to about 0.2 μm, improving their fatigue strength.

CONCLUSIONS

The performed investigations concerning the fatigue of the AlZn6Mg0.8Zr alloy 7003 series and the analysis of the results of the mechanical properties, as well as metallographic observations allow to draw the fallowing conclusions:

1. The fatigue strength of the tested samples of aluminium of the kind 7003 subjected to low-temperature thermomechanical treatment changes linearly within the range of low-cyclic loads from the value of stresses σ_a amounting to about 190 MPa to about 160 MPa, corresponding to the number of cycles of oscillating bending N_f from about $6 \cdot 10^4$ to about $2 \cdot 10^6$.
2. The applied variant of thermomechanical treatment affects positively the refinement of the grains in the solution-α of the investigated alloy and increases the amount and dispersion of precipitations of intermetallic phases, mainly of the Mg_2Si or Al_2Mg type.
3. The fractures of the tested samples are after fatigue tests in the range of low-cyclic temporary fatigue strength principally transcrystalline quasi-cleavage with the cleavage planes without any traces of plastic deformation and zones of intercrystalline cracking.
4. In the zone of high-cycling fatigue and permanent fatigue strength the fractures of the tested samples indicate a distinct share of plastic deformation on the surface of the jogs affecting potentially the stochastic planes of cleavage.
5. The microfractography of fatigue fractures of the analyzed samples indicate probably an interlocking mechanism of cracking of the Al-Zn-Mg alloy.

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