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MATERIALS FOR AEROSPACE TECHNOLOGY

Characteristic Features of Physical and Mechanical Properties of Ultrafine-Grained Al–Mg Alloy 1560

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Abstract—Specimens of Al–Mg alloy 1560 of ultrafine-grained structure were obtained by the method of severe plastic deformation based on multiple equal-channel angular pressing. Impact on physical and mechanical properties of the processed material and fracture pattern of specimens was studied. Tensile tests showed an increase of the offset yield strength and resistance to rupture with decrease in the ultimate deformation. The obtained specimens have increased microhardness values compared to the initial ones. It was established that the last cycle of pressing determines the structural orientation of macroscopic shear bands occurring at an angle to the specimen longitudinal axis while passing connection of channels. It affects the physical and mechanical properties of the material and fracture pattern. The quality control of the obtained specimens by the method of ultrasonic defectoscopy and X-ray tomography confirmed the absence of macro- and microdefects when following the matched optimal regime of processing.

Keywords: ultrafine-grained structure, aluminum alloy, severe plastic deformation, mechanical properties, light alloys

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INTRODUCTION

Many contemporary researchers observed improvement of properties of construction materials and alloys when processing by methods of severe plastic deformation (SPD) [1–5]. With SPD, the internal structure of many construction materials is refined to ultrafine-grained or nanostructural states, at which point their physical and mechanical properties are changed and strengthening takes place. The strengthening effect is marked by increase in microhardness, yield strength, and ultimate strength. In addition, the maximum degree of strain to fracture is changed and the operational life and endurance strength are improved. Implementation of SPD is possible by various methods: at local zones at surfaces of specimens and throughout the material. The method of equal channel angular pressing (ECAP) became a frequent practice that allows one to obtain three-dimensional samples of the material with ultrafine-grained (UFG) structure. The appropriate optimal pressing regime should ensure uniform refining of the alloy microstructure without formation of micro- and macrodefects and without cracking of the specimen material [5].

The Al–Mg construction alloy 1560 came into common use in the aircraft, automobile, and space industry. Change in its physical and mechanical properties due to modification of its internal structure up to nano- and UFG states will allow one to improve operational efficiency of parts of critical mechanisms in different operating conditions.

Study of special aspects of severe plastic deformation impact at elevated temperatures on the structure and physical and mechanical properties of the alloy 1560 is the goal of the given research.

MATERIALS AND METHODS

Prismatic workpieces with dimensions of 8 × 8 × 40 mm^3 were made from a bar of hot-rolled coarse-grain alloy 1560 (with a composition of 92.0 wt % Al, 7.0 wt % Mg, 0.7 wt % Mn and other impurities) for processing and following study. SPD processing of prismatic workpiece according to the ECAP scheme

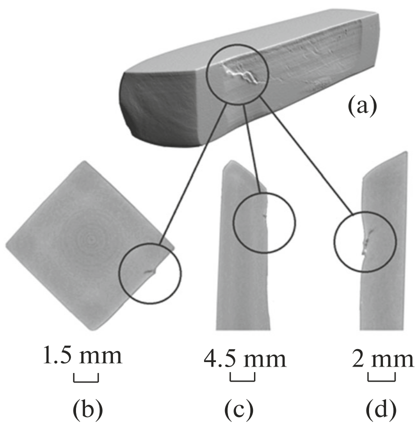

Fig. 1. Results of X-ray tomography: (a) isometric projection of the voxel three-dimensional model ; (b) front section; (c) left longitudinal section, (d) right longitudinal section.

until the UFG state was performed en route B_c enclosing the rotation around the longitudinal axis by 90 degrees with repeated pressing at the temperature of 473 K and pressing speed of 15 mm/min with the application of a high-temperature molybdenum disulfide based lubricant [5]. It was expected that the chosen pressing scheme is favorable to development of a uniform structure throughout the specimen material of the UFG structure, thereby providing isotropy of mechanical properties [6]. When processing workpieces of the material studied, the servohydraulic testing machine INSTRON 40/50-20 with a heat chamber and option of precise regulation of pressing speed and loading force up to 50 kN, was used.

A nondestructive technique with use of X-ray tomography on the modern research tomograph YXLON Y. Cheetah was recommended in the study to control quality of the specimens obtained after processing [7].

After processing of prismatic workpieces, a set of studies for determination of physical and mechanical properties of the material was carried out which included texture and microstructure analysis, microhardness testing, determination of sound speed estimation for fixation of the elastic modulus, and uniaxial tension of plane specimens.

The study of texture and microstructure of material before and after processing was performed by electron backscattered diffraction techniques (EBSD) with a Tescan Vega II LMU electron microscope fitted with an electron backscattered diffraction add-on device. The surface of the studied specimens was prepared by the method of mechanical prepolishing and ion etching on an ION SLICER EM-09100 apparatus. The analysis of the obtained data was performed with the licensed software HKL-Channel 5.

The study of the alloy mechanical texture after SPD was performed on an Olympus GX optical inverted-stage microscope. To prepare for optical microscopy, chemical etching of working section of the plane specimens, made for uniaxial tension experiments, was used.

Microhardness measurement experiments HV (Vickers hardness test) were performed in accordance with standard ISO 6507-1:2005 at the lateral surface of prismatic workpieces at various sections along the pressing axis. A Shimadzu HMV G21ST automatic microhardness tester was used. Indentation was performed at loading of 50 g and holding time of 10 s. More than 100 measurements were performed for each specimen. The specimens were prepared according to the standard technique with abrasion machining and polishing up to a mirror-like faultless surface with peak to trough height $R_z = 0.1$ μm and $R_a = 0.025$ μm.

The passage velocity of the longitudinal elastic wave between opposite ends in prismatic workpieces was measured with a HARFANG VEO 128:16 ultrasonic defectoscope with a frequency sensor of 5 MHz.

Standart plate-type specimens for tension with dimensions of the gauge length of 10 mm, thickness of 1 mm, width of 3 mm, and the spherical radius of 2.5 mm were cut of prismatic workpieces along the pressing axis by the electroerosion cutting method. The uniaxial tension experiments were performed on an INSTRON 40/50-20 multiple purpose servohydraulic testing machine with strain rate of 0.001 s^{-1} and test temperature of 25°C. Tension loads of the specimens were registered within the accuracy of 0.05% with a Dynacell universal sensor.

RESULTS AND DISCUSSION

The presence of defects on the internal surface, porousness, microfissures, and voids

throughout the processed specimens of the alloy were estimated by modern methods of X-ray tomography. The result of X-ray tomography is a three-dimensional image of the object in the form of a voxel model by means of which one can obtain to micron accuracy the image of any surface or internal section [7].

A voxel model of the prismatic workpiece with a crack after nonoptimal pressing conditions is presented in Fig. 1. The model is presented in isometric projection and three sections. The surface defect in the step-shaped form is, when studied in detail, actually a crack going from the surface into the workpiece. Workpiece with similar macrodefects were thrown out. Results of X-ray tomography confirmed that, with technology compliance of implementation SPD described in [5], the material structure after processing has neither macro- nor microdefects.

The longitudinal velocity of sound in the alloy in the as-received state and after processing varies in the range of 0.04% and is 5440 ± 2 m/s, which corre-

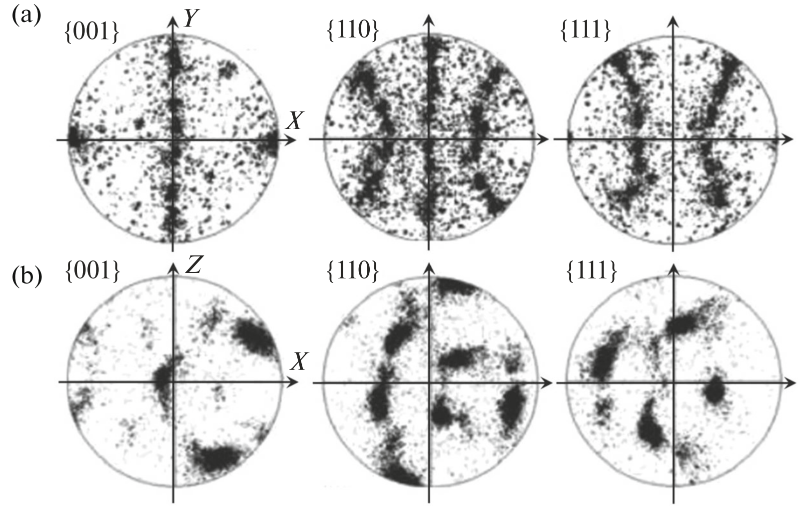

Fig. 2. Direct pole figures of the aluminum alloy 1560 specimen: (a) as-received, (b) after four ECAP passes.

sponds to Young's modulus of elasticity equal to 78 ± 0.03 GPa. It is known that the presence of defects significantly reduces the speed of acoustic waves. In view of the fact that after processing the speed of sound in the material did not change, the data of ultrasonic examinations complement results of X-ray tomography and confirm the soundness of the processed material.

The studied alloy 1560 in the macrocrystalline state has structure with grains in the range from 2 up to 400 μm with the average grain size of 50 μm. Large grains for the most part have an elongated form and are oriented along the direction of rolling. After ECAP processing (4 passes) with the optimal regime, the UFG structure is formed throughout the specimen with the average grain size of 3 μm.

When analyzing straight pole figures (Fig. 2), it is apparent that the symmetrical cubic texture dispersive along *Y*, which is changed owing to ECAP by the texture {110}⟨001⟩, symmetric with respect to *X* is observed in specimens in the as-received state. The direction perpendicular to them in the initial state has a distinct cubic element that is defused after processing. Change in the workpiece movement in the press mold channel by 90 degrees results in diffusion of orientation in the direction of the bending axis and loss of the distinct axial cubical texture specific to the initial state. Such reorientation of grains differs from texture changes caused by classic methods of pressure metal treatment. With such a scheme, the shear in the region of connection of channels plays an important role. A nonuniform all-round compression in the end contributes to maximum outward flow in direction of the connected channel in conjunction with the bend.

Results of metallographic studies of the processed material are presented in Fig. 3 in the form of mechanical texture after chemical etching. One can see the texture specific to the ECAP method, directed at the angle of the pressing axis, caused by formation of macroscopic shear bands when passing through connection of the channels at the last stage of multipass pressing. The refined grains are oriented by the shear bands. The grains appear to be severely deformed, which corresponds to path flow B_c that ensures maximal grain refinement, which was verified by other studies [6, 8].

Measurement of the studied material microhardness value showed that after ECAP processing, it increases with nonuniform distribution throughout the specimens. Results of the microhardness value changes at the lateral side along the axis of the prismatic workpiece after four passes of pressing are presented in Fig. 4. The relation of the distance of measuring area Δd (mm) from the edge to overall length d_0 is plotted on the x axis. Data extraction and its smoothing were performed when processing the experimental results. In doing so, fidelity intervals were determined for all statistical data as well. After four passes, the microhardness increases on average by

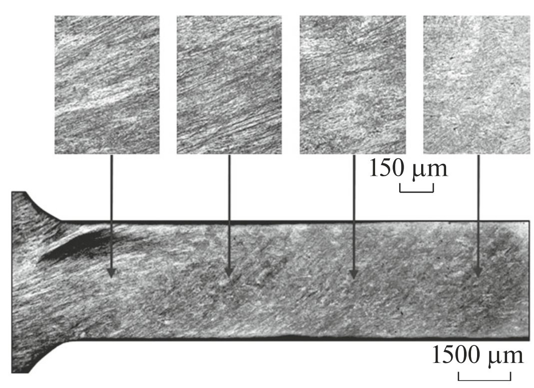

Fig. 3. Mechanical texture of the alloy after four ECAP passes on the tensile specimen surface.

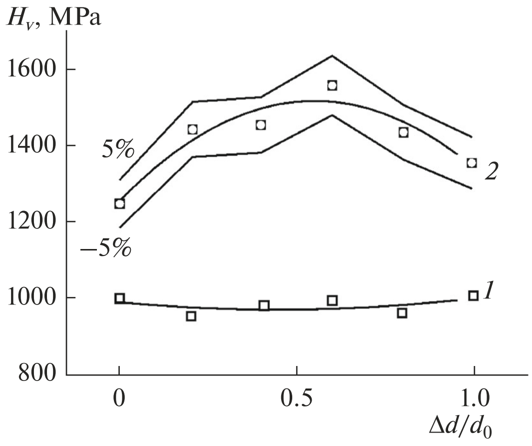

Fig. 4. Microhardness comparison of the alloy 1560: (*1*) as-received, (*2*) after four ECAP passes.

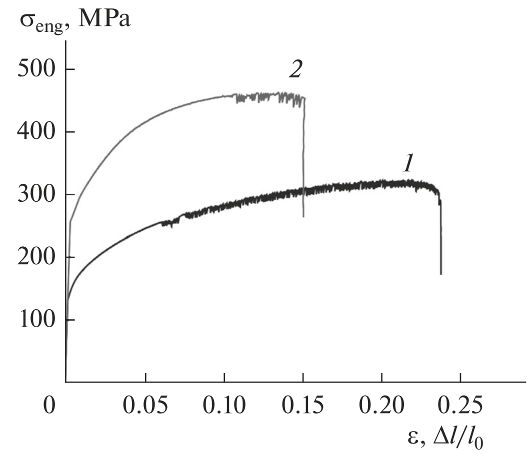

Fig. 5. Engineering stress-strain curves for the 1560 alloy: (*1*) as-received, (*2*) after four ECAP passes.

50% and its maximum value reaches 1550 ± 30 MPa with the initial microhardness of 1000 ± 50 MPa.

In the central area of the specimens, the microhardness is somewhat higer (up to 10%) in comparison to the average value. This is due to nonuniform accumulation of plastic deformations and their maximum values in the central part of specimens, which is confirmed by theoretical results [9].

Engineering stress-strain curves for uniaxial tension of the plane specimens of the alloy 1560 in the as-received condition and after four ECAP passes are presented in Fig. 5. A sawlike profile in the region of the plastic flow is a specific feature for load curves of aluminum alloys [10] indicating discontinuous yielding with uniaxial loading due to the Portevene–Le Chatelier effect. In experiments, sawlike profiles are not observed throughout the plastic flow. For the alloy in the as-received condition, this stage begins from 0.06 of structural strains. For the processed alloy in UFG condition, there occurs the shift into large deformation domain and the stress relieving starts from 0.1.

A simultaneous increase in the yield strength by 80% (from 150 to 270 MPa), increase in ultimate strength by 44% (from 320 to 460 MPa), and decrease in elongation at fracture in strain conditions by 30% (from 0.23 to 0.15) are observed for the alloy 1560.

When estimating the fracture pattern of specimens for uniaxial tension from the initial and processed material, it was observed that the specimen of the initial material came apart perpendicularly to the axis of tension without noticeable necking. At the same time, the specimen made of the processed SPD alloy in UFG condition came apart at the angle of 45° to longitudinal axis with necking. The difference in the character of fracture is explained by the change throughout the material of the specimens after ECAP processing.

The fracture angle coincides with direction angles of macroscopic shear bands in the revealed mechanical texture presented in Fig. 3 and corresponding grain structure orientation in the working part of the specimen before the tensile test.

CONCLUSIONS

Owing to the orthogonal equal channel angular B_c pressing, when following the optimal regime of processing, a defect-free internal ultrafine-grained structure with the average grain size of 3 μm with the initial one of 50 μm is formed in the alloy 1560. In this case, the initial diffused cubic texture changes into symmetrical deformation shear texture {110}⟨001⟩. The last pressing cycle determines the orientation of the structure and macroscopic shear bands occurring at the angle to the specimen longitudinal axis while passing connections of channels, which affects the mechanical properties of the material and fracture pattern.

The obtained ultrafine-grained structure of the studied alloy provides an increase in its microhardness by 50%, offset yield strength by 80%, and ultimate strength before fracture by 44% compared to the corresponding values of the initial coarse-grain alloy and does not affect the change in value of the elastic modulus. Effects of increase in microhardness, yield strength, and rupture strength with tension with simultaneous decrease in ultimate deformation to fracture are characteristic features of Al–Mg alloys after SPD without annealing [11, 12].

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