Physical and computer simulation of severe plastic deformations on shear-compression testing of AMg6 (АМг6) aluminium alloy

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A deformable AMg6 (АМг6) aluminum alloy of Al – Mg system is characterized by good plasticity, high corrosion stability and good welding capacity. That's why it is widely used in welded constructions of rockets and space vehicles. However, the essential weakness of AMg6 alloy is its rather low strength. Therefore, the topical task is a development of new non-cutting shaping technologies which can guarantee the improved strength properties of AMg6 alloy. One of the possible ways to solve this problem is to form in the melt a fine-graded or ultrafine-graded structure through the application of severe plastic shear-compression deformations by asymmetric cold rolling technology. To emulate such a technology and to define optimal deformation parameters, which provide the fine-graded or ultrafine-graded structure formation, a technique of high-cycle deformation of laboratory specimens according to a shear-compression scheme has been implemented on a Shimadzu AG-IC 300 kN precision universal testing machine. Special specimens have been produced in the shape of parallelepipeds 50 mm in height with a square cross-section of dimension 25×25 mm with two parallel notches in 6 mm wide and 10 mm depth, implemented at the side surface at angle of 45 degrees to vertical axis with fillet radii of 3 mm.

The objective of this work has been to experimentally test this technique and to study the distinctive features of changes of the AMg6 structural alloy structure and microhardness on achievement severe plastic deformations during shear-compression testing. As a result of the carried out investigations, it is established that ultimate plastic strains of the AMg6 aluminum alloy in a cold state are restricted by the value of true deformation $e = 1$, on achievement of which the cracks formation and material destruction take place. It is shown that high-cycle warm deformation of the AMg6 aluminum alloy in a shear-compression scheme with achieving severe plastic deformation $e = 4$ at a temperature of 200 °C leads to formation of fine-graded structure and significant increase of *HV* microhardness up to ~1350 MPa.

Key words: aluminum alloy, severe plastic deformation, shear-compression testing, physical simulation, finite-element method, microstructure, microhardness.

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Introduction

Making more elaborate materials for aircraft building and aerospace industry is connected with a problem of searching new welding, not hardenable by heat-treatment aluminum alloys of Al – Mg system with higher strength characteristics as compared with that of existing industrial analogues [1]. A deformable AMg6 aluminum alloy of the Al – Mg system is characterized by good plasticity, high corrosion stability in various mediums and good welding capacity. That determines its wide usage in most welded constructions of rockets and space vehicles [1–3]. At the same time, the essential weakness of the AMg6 alloy is its rather low strength: a guaranteed yield stress of the AMg6 alloy half-finished products, being the main design performance for the majority of constructions, lies within the range of 120–155 MPa depending on the semiproduct type [1]. Notwithstanding the reasonably useful increase of magnesium dissolubility in aluminium as temperature rises, the AMg6 alloy strengthening on quenching is rather low, therefore it is among not hardenable by heat-treatment alloys along with the other ones of the Al – Mg system. The main means of improving its strength characteristics is cold deformation (strain work hardening). Therefore, the topical task is a development of new non-cutting shaping technologies which can guarantee the improved strength characteristics of the AMg6 alloy.

One of the possible ways to drastically increase (2–3 times) the strength of aluminum alloys is to form in them a fine-graded or ultrafine-graded structure through the application of severe (intensive) plastic deformations ($e \geq 1$), for example, by asymmetric rolling processing with a purposively assigned mismatch of the rolls peripheral velocities [4–12]. At that, the key condition to reach severe plastic deformations is a synergetic effect gained from the joint action of shearing and compressive strain.

To emulate the asymmetric rolling technology, in work [13] there has been developed a shear-compression testing procedure for specimens of particular geometry in order to determine optimum deformation parameters providing formation of the fine-grained or ultrafine-grained structure.

The objective of this work has been to experimentally test this technique and to study the distinctive features of the AMg6 structural alloy structure and microhardness changes on achieving severe plastic deformations during shear-compression testing.

Materials and methods of investigations

Physical simulation of severe plastic deformations within the range of $e = 1–4$ has been carried out with the use of a high-cycle laboratory specimen's shear-compression deformation technique on a Shimadzu AG-IC 300 kN precision universal testing machine. According to the procedure, special specimens have been produced in the shape of parallelepipeds 50 mm in height with a square cross-section of dimension 25×25 mm with two parallel notches in 6 mm wide and 10 mm depth, implemented at the side surface at angle of 45 degrees to vertical axis with fillet radii of 3 mm (Fig. 1). Specimens have been made of commercial AMg6 aluminum alloy manufactured by "Kamensk Uralsky Metallurgical Works" Public Corporation. Chemical analysis of specimens (Table) has been implemented on a SPECTROMAXx optical emission spectrometer. The specimens have been produced on a BZT PFE-500PX engraving machine with the use of an AL-2B-R3.0 ZCC-CT ball mill for aluminum.

Before shear-compression testing, an annealing of specimens has been fulfilled at a temperature of 320 ± 10 °C for 30 min with slow cooling in a furnace up to room temperature. Structure of an AMg6 macrocrystalline alloy after the annealing has consisted of grains of elongated shape (Fig. 2) with average dimensions as follows: 239 μm (longitudinal) and 24 μm (transversal).

Two variants of the shear-compression testing conditions have been considered, namely: 1) in a cold state at a temperature of 20 °C; 2) in a warm state at a temperature

Actual content of chemical elements in AMg6 alloy, % (wt.)

Si	Fe	Cu	Mn	Mg	Zn	Ti	Be	Al
0.14	0.25	0.03	0.73	6.2	0.08	0.04	0.0008	The rest

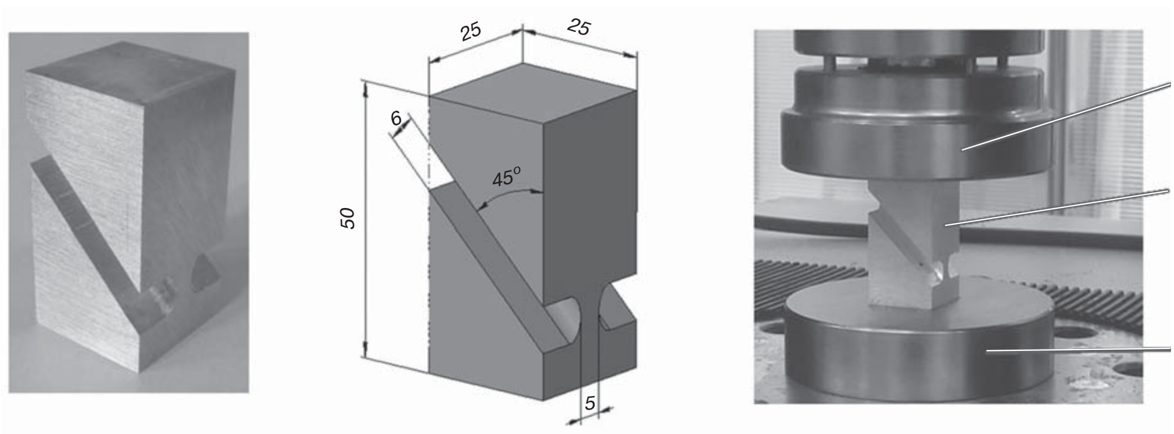

Fig. 1. Overall view (*a*), dimensions of the specimens (*b*) and testing scheme (*c*)

Fig. 2. The microstructure of the annealed AMg6 alloy (×100)

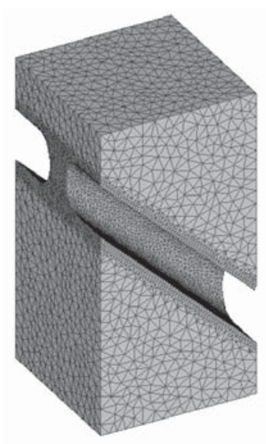

Fig. 3. Grid of final elements

of 200 °C with warming-up of the specimens after each deformation cycle.

Computer simulation of severe plastic deformations on the AMg6 aluminum alloy shear-compression testing has been carried out by finite-element method with the use of the license DEFORM 3D process simulation system. The following assumptions for computer simulation have been accepted: 1) the deformable medium is strengthening and plastoelastic; 2) the dies are absolutely hard; 3) the contact friction law — that of Coulomb; 4) the deforming conditions are isothermal (20 or 200 °C); 5) the contact friction coefficient has been accepted equal to 0.08 on the basis of calibration versus experimental data, which has met the conditions of deformation with grease. In all calculation variants for a deformable specimen, grid of final elements (80,000–100,000) has been set in a form of tetrahedrons with thickening coefficient in the notch area equal to 10 (Fig. 3). To describe rheology of the AMg6 alloy there have been used the yield locuses (Fig. 4), determined by experimental data in accordance with the procedure reported in works [14, 15]. Relying on computer simulation, the intensity level of metal deformation in the notch area has been estimated as well as calculated and actual values of strain energy have been compared in order to control adequacy of the results. According to the procedure, in the course of physical and computer simulation the specimens have been first of all deformed with reduction in thickness throughout the height in 5 mm (per cent reduction is 10%), that is from 50 to 45 mm, with the upper die displacement speed of 10 mm/min (Fig. 5). As a result, the parallelepiped has taken a beveled shape (Fig. 5, *b*). Then the specimens have been rotated through 90° in vertical plane (Fig. 5, *c*) and once again pressed out in order to obtain quasiprime parallelepiped shape with a square cross-section of dimension 25×25 mm (Fig. 5, *d*). The given sequence has represented a single shear-compression deforming cycle with a true deformation value e equal to 1.0 in the notch area. Furthermore, the cycle has been repeated 2, 3, 4 times until respective reaching 2, 3, 4 units of true deformation in the notch area.

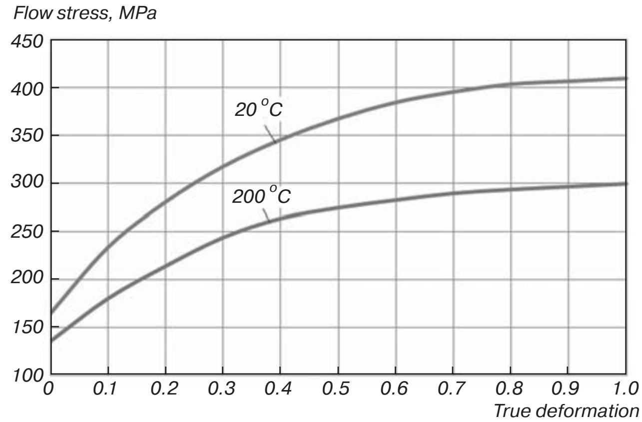

Fig. 4. Yield locuses of the AMg6 alloy under computer simulation

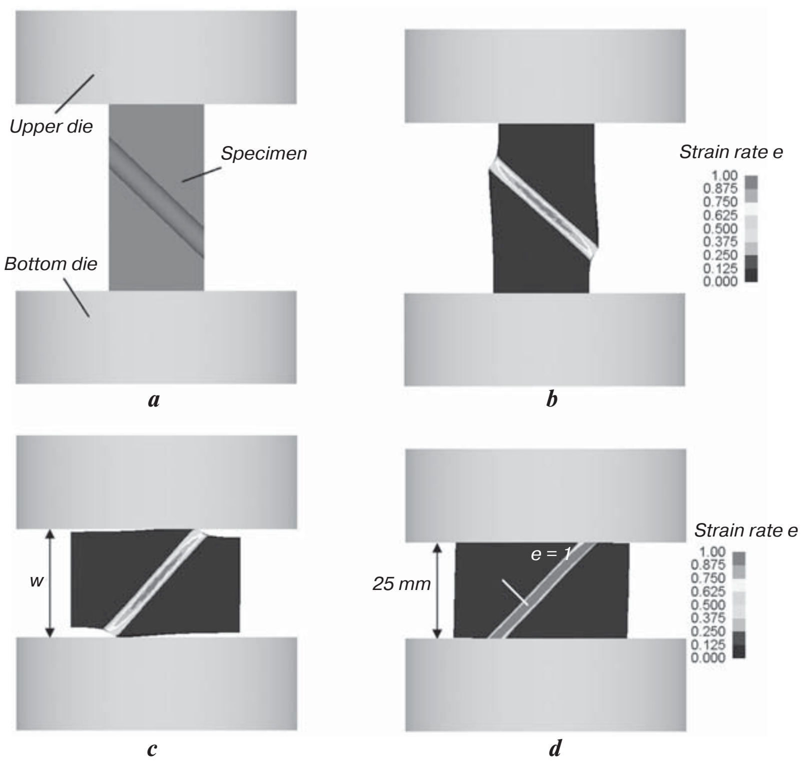

Fig. 5. Scheme of the specimens shear-compression deformations in a single cycle

Microstructure of laboratory specimens has been investigated in Nanosteels Research Institute of Nosov Magnitogorsk State Technical University. To fulfill microanalysis, the cross-cut microsections have been made of specimens with the use of their pressing in to Transoptic pitch using a Simplimet 1000 automatic mounting press at a Buechler sample preparation line. To reveal microstructure, the slice surface has been etched by the polished surface submersion into a bath with reagent consisting of, %: HF — 1.0, HF — 1.5, HNO_3 — 2.5, H_2O — 95. Metallographic analysis has been implemented on a Meiji Techno optical microscope at magnifications up to 1000 times through the use of the Thixomet PRO computer image analysis complex. Microstructure at magnifications above 1000 times has been studied in secondary electrons by means of a JEOL JSM 6490 LV scanning electron microscope. The Vickers microhardness HV has been determined on a Buchler Micromet hardometer by pressing in of the diamond pyramidion with the angle between the opposite faces of 136° at the load of 200 g and load duration of 10 s in accordance with the State Standard GOST 9450 (ГОСТ 9450).

Results of simulation and their discussion

Comparative analysis of calculations data obtained by finite-element method (FEM) and experimental values of deformation has demonstrated high convergence, which testifies correctness of rheology of the AMg6 alloy and conditions of contact friction during physical modeling (Fig. 6).

In the course of the experiments it has been ascertained that during the progress of shear-compression testing of specimens in a cold state (at room temperature), the cracks formation and destruction of material take place in the notch area in the second cycle of deforming at the value of true deformation $e > 1$ (Fig. 7). On the other hand, in conditions of warm deformation at a temperature of 200 °C, cracks in the notch area haven't been observed even after four cycles of deforming with accumulated deformation $e = 4$. The given fact is in quite a good agreement with the results of work [16], the authors of which have experimentally established, using the method of equal channel angular pressing (ECAP) as an example, that severe deformations at temperatures below ~200 °C leads to cracking of the AMg6 alloy billets.

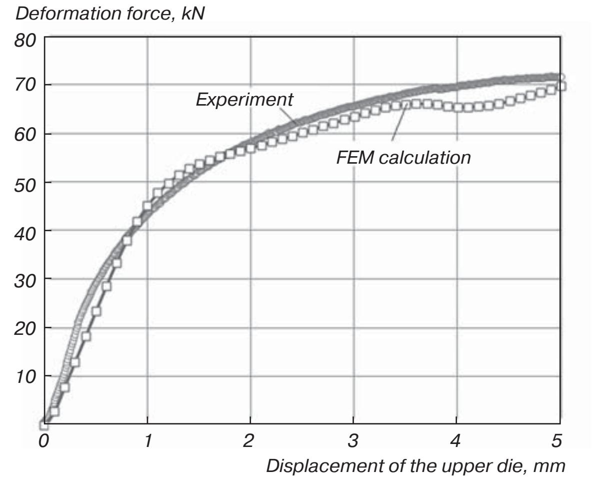

Fig. 6. The deformation force change during the shear-compression testing in the course of physical and computer simulation (the first cycle at a temperature of 20 °C)

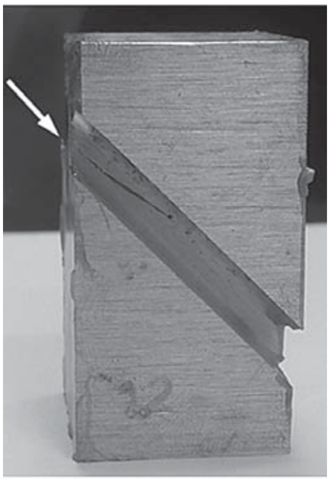

Fig. 7. Forming the crack (indicated with the arrow) during the second cycle of deforming ($e > 1$) at a temperature of 20 °C

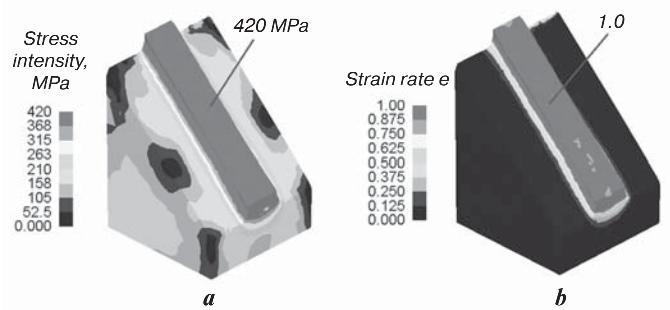

Fig. 8. Fields of the stress intensity (*a*) and strain rate (*b*) in the specimen after the first cycle of the shear-compression testing (at a temperature of 20 °C)

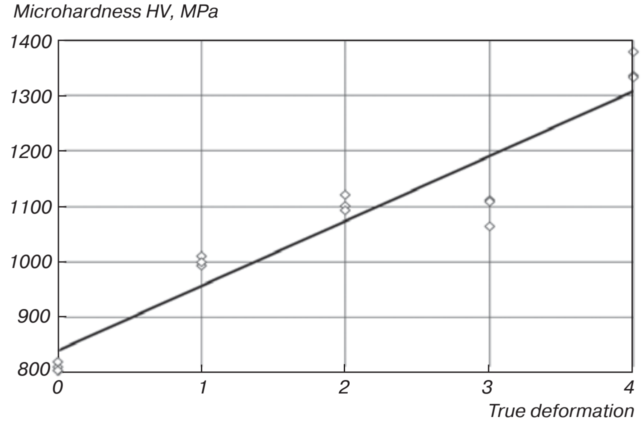

Fig. 9. The AMg6 alloy microhardness after shear-compression processing at a temperature of 200 °C

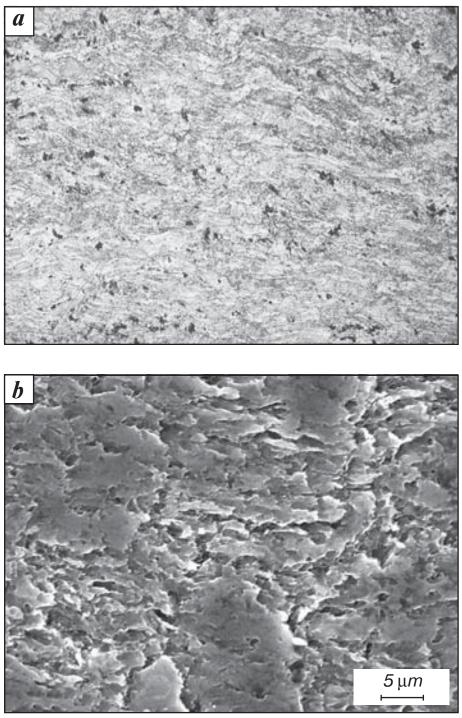

Fig. 10. The AMg6 alloy microstructure after 4 cycles of the shear-compression testingat a temperature of 200 °C:
a — with a light microscope (×100); *b* — with a scanning microscope (×3000)

Analysis of deflected mode of the metal have revealed that plastic deformation in case of a shear-compression testing is localized in the notch area with homogeneous distribution of stress intensity and strain rate (Fig. 8). Achieving a severe true deformation ($e = 1$) in a single cycle of testing at a relatively moderate 10% height specimen reduction is provided by significant role and contribution of the shear information.

The results of microhardness measurements of the AMg6 alloy after its shear-compression handling at a temperature of 200 °C have showed that *HV* value increases approximately 64% from initial ~820 to ~1350 MPa after four strain cycles with accumulated deformation $e = 4$ in the notch area (Fig. 9). The pronounced increase is connected to the formation of the fine-graded structure of alloy (Fig. 10). The obtained microhardness value is substantially higher than that after the AMg6 alloy proceeding by the ECAP method at a temperature of 200 °C in 4 passes with epy achieved maximum *HV* value of ~1050 MPa [16]. Given result may evidence the fact that severe plastic deformation owing to realization of the shear-compression scheme may cause more intensive strengthening of the AMg6 alloy in comparison with ECAP processing according to the simple shear scheme.

Conclusions

Ultimate plastic deformations of the AMg6 aluminum alloy in a cold state are restricted by the true deformation value $e = 1$, on reaching which there take place cracks formation and material destruction. The warm deformation conditions at a temperature of 200 °C are the rational ones. The high-cycle warm deforming the AMg6 aluminum alloy in a shear-compression scheme with achieving severe plastic deformation $e = 4$ at a temperature of 200 °C leads to formation of fine-graded structure and significant increase of *HV* microhardness up to ~1350 MPa.

The presented shear-compression test procedure for specimens of a special form can be used to emulate the asymmetric rolling technology in order to determine optimum deformation parameters providing formation of the fine-grained or ultra fine-grained structure and improved mechanical properties of aluminum alloys.

M. K. Sverdlik has participated in the investigations.

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