Experimental study of macroscopic localization of plastic flow in Al-Mg alloy under complicated stress-strain state

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Abstract. The main objective of this work is to investigate the spatial-time inhomogeneity due to the jerky flow during plastic deformation of Al-Mg alloy under complex stress conditions. The use of specimens in the form of plates with a rigid circular rim and a reverse curvature rim was considered. Experimental data on the evolution of inhomogeneous strain and temperature fields have been obtained, illustrating the processes of initiation and propagation of deformation bands of the localized plastic flow by using the digital image correlation and infrared thermography.

1. Introduction
Forecasting of the behavior of constructional metal materials under set service conditions, as well as designing of engineering structures and ensuring their high reliability and strength require understanding of the theory of the non-elastic deformation and destruction under the spatiotemporal inhomogeneity of plastic yielding. The macro localization of plastic yielding of solids and banding processes cause the significant reduction of the surface quality of used materials and, correspondingly, to the significantly reduced plasticity and strength and to the spontaneous macro destruction of elements of critical structures and facilities.

It shall be noted that in the scientific literature, inadequate attention is paid both to experimental studies and to theoretical description of regularities related to the spatiotemporal inhomogeneity of elastic deforming with taking into account the influence of a nature of the compound stress-strain state (SSS) of a material, although it is known that in most cases, the material service implies compound thermomechanical impacts [1, 2].

Mechanical tests carried out under the compound stress state imply significant procedural difficulties and technical restrictions of loading schedules and modes, methods of reaching of controlled SSS in a working area of a specimen, as well as procedures of recording and interpretation of results obtained [1]. The development of methods of and scientifically-based approaches to experimental studying is of interest; these methods and approaches shall be used for studying of regularities and peculiarities of the non-elastic behavior and destruction of modern constructional metals and allows, based on the use of original complex-geometry specimens [3-6]. Required SSS is created in the working are of these specimens, and the control of loading system characteristics is ensured [7, 8].

The purpose of this work is the experimental studying of peculiarities and effects of plastic yielding of an aluminum-magnesium alloy depending on a nature of the compound stress state, as well as in bides with raisers. Proposed test methods involve the use of circular-plate specimens placed into a rigid
circular rim and an inverted-camber rim [9]. During the uniaxial tension of these specimens, the flat stress state arises in the plate, with differently signed principal stresses.

2. Verification of specimen geometrical parameters

The non-uniform stress state, i.e. the tension along the axis Oy (along the loading axis) and compaction along the axis Ox arises in a central part of the rigid-circular rim plate. In the central part of the rigid inverted-camber rim, the biaxial tension is available. A relation of longitudinal and transverse stresses is determined by geometrical parameters of the specimens: rim width and thickness and its radiuses of curvature.

The geometry was selected using numerical modeling in the Ansys software package. The mathematical description of the problem included equilibrium equation without bulk forces taken into account (1), geometrical Cauchy relations for small strains (2) and defining relations for isotropic material (3).

\[
\sigma_{ij}(r) = 0 \quad (1)
\]

\[
\epsilon_{ij}(r) = \frac{1}{2} \left( u_{ij}(r) + u_{ji}(r) \right) \quad (2)
\]

\[
\sigma_{ij}(r) = E \cdot \epsilon_{ij}(r) \quad (3)
\]

Elastic parameters were set using the Young’s module \( E = 71 \) MPa and Poisson's ratio \( \nu = 0.3 \). The numerical calculation was carried out using twenty Solid 186 finite elements. Due to the symmetry, the solution was carried out for a half-specimen. The studied area was divided into finite elements: 28,520 elements for the model of the rigid-circular rim specimen and 22,673 elements for the model of the inverted-camber rim specimen.

The specimens were fastened by means of the restriction of movements of their side face along the transverse axis Oy and of the bottom face along the longitudinal axis Oy; additionally, the terminal point of the bottom face was fastened on the axis Oz. A 1 cm tensile displacement along the longitudinal axis was applied to the top face. Figure 1 and figure 2 show specific fields of transverse and longitudinal stresses for the rigid-circular rim specimen and the inverted-camber rim specimen, correspondingly. Relation of the longitudinal and transverse stresses in the central part of the rigid-circular rim plate:

\[
\frac{\sigma_x}{\sigma_y} = \frac{0.45 \cdot 10^6 \text{Pa}}{-0.14 \cdot 10^6 \text{Pa}} = -3.21. \quad (4)
\]

Relation of the longitudinal and transverse stresses for the inverted-camber rim specimen:

\[
\frac{\sigma_x}{\sigma_y} = \frac{0.42 \cdot 10^6 \text{Pa}}{0.16 \cdot 10^6 \text{Pa}} = 2.63. \quad (5)
\]

Based on numerical modeling results, the specimens were milled; in some specimens, a through round hole ø 6.0 mm was added in the central part of the plate. Figure 3 shows sketches of the final configuration of specimens.
Figure 1. Fields of transverse (a) and longitudinal stress (b) for the rigid-circular rim specimen

Figure 2. Fields of transverse (a) and longitudinal stress (b) for the inverted-camber rim specimen

Figure 3. Sketches of the final configuration of specimens
3. Mechanical tests and processing of their results
The uniaxial-tension mechanical tests were carried out using an Instron 5989 electromechanical test system with the constant kinematic loading speed of 5.0 mm/min, at a room temperature. The specimens were made of 12 mm thick AMg6b flat products. The chemical composition of the Al-Mg alloy is as follows: Mg – 6.1 %, Mn – 0.6 %, Fe – 0.2 %, Si – 0.1 %, Cu – 0.1 %, and Zn – 0.1 %. Strain fields were recorded using a Vic-3D contactless three-dimensional digital optical system with high-resolution cameras (Prosilica, 16 MP). Temperature fields were analyzed using a FLIR SC7700M infrared imaging system with a CMT (cadmium-mercury-tellurium) detector. It shall be noted that during tests, the loading procedure and imaging of temperature-and-strain fields were synchronized by means of a NI USB-6251 (ADC unit).

The effectiveness assessment of the application of special-geometry specimens is of interest. In the working area of this specimens, the compound stress state is implemented: for the rigid-circular-rim plate, the tension along the axis Oy and the compaction along the axis Ox (Figure 5), while for the inverted-camber rim specimens, the tension along both axes (Figure 6) are correspondingly recorded.

Figure 4. Experimental study of the macroscopic localization of plastic flow under complicated stress-strain state: 1 – the Instron 5989 electromechanical testing system, 2 – the 3D digital image correlation system Vic-3D, 3 – the infrared camera SC7700M

Figure 5. The dependence of longitudinal (curve 1) and transverse (curve 2) deformation on time during uniaxial tension of the plate with the rigid circular rim (a) and corresponding longitudinal ($\varepsilon_{yy}$) and transverse ($\varepsilon_{xx}$) strain fields
Figure 6. The dependence of longitudinal (curve 1) and transverse (curve 2) deformation on time during uniaxial tension of the plate with the inverted-camber rim (a) and corresponding longitudinal ($\varepsilon_{yy}$) and transverse ($\varepsilon_{xx}$) strain fields.

Based on the data calculated by the digital image correlation system, the ‘strain-time’ curves are constructed that illustrate the ratio of longitudinal and transverse deformations in the central part of the specimens as shown on the figure 5 (a) and figure 6 (a). It should be noted that the biaxial tension for the plate with the inverted-camber rim is fixed only on the elastic stage of the deformation diagram.

Figure 7 shows loading diagrams obtained for the rigid-circular rim specimens and the inverted-camber rim specimens (curves I), as well as for the specimens with additional concentrators in the central part (curves II). On the plots $P \sim u$, starting of the discontinuous yielding effect due to the Portevin-Le Chatelier (PLC) effect is recorded, followed by the banding process (Figure 8). At the start moment of the jerky flow (point 1, figure 7, a) the initiation of the macroscopic localization of plastic deformation is observed on the specimen surface. The occurrence of the deformation band (the PLC band) is recorded both on the deformation field and on the temperature field as well. Inhomogeneity of plastic deformation cause the drop on the loading curve.

Figure 7. Diagrams of loading samples in the form of plates with a rigid circular rim (a) and a reverse curvature rim (b) - curves I, plates with a through hole in the working part - curves II.

As an example, the figure 9 and figure 10 show characteristic inhomogeneous fields of the longitudinal strain rates, which illustrate the patterns of formation of deformation bands and of the localized plastic flow in Al-Mg alloy due to the PLC effect under complicated stress-strain state and in the bodies with stress concentrators.
Figure 8. Inhomogeneous fields of local longitudinal strain rates (a) and change in temperature field (b) at the time of formation of a single deformation band due to the Portevin-Le Chatelier effect.

Figure 9. Inhomogeneous fields of local longitudinal strain rates illustrated the PLC effect for the plate with a rigid circular rim (a) and the plate of the same geometry with a hole (b).

Figure 10. Inhomogeneous fields of local longitudinal strain rates illustrating the PLC effect for the plate with a reverse curvature rim (a) and the plate of the same geometry with a hole (b).
4. Conclusions
The evolution analysis was carried out for non-uniform displacement fields, strains and local straining rates; they characterize initiation and propagation processes related to the strain bends of localized plastic yielding caused by appearing of the discontinuous yielding effect, Portevin-Le Chatelier effect, under the compound stress state and upon available additional stress raiser in the form of the round hole in the specimen center.

Fig. 8 shows a single band of localized plastic yielding (PLC band), which was recorded on the plate surface by optical systems analyzing temperature-and-strain fields. The process of PLC banding runs with a slight local temperature elevation caused by active plastic straining (Figure 8, b), thus, the high sensitivity mode, applicable for analyzing of small temperature changes, was used for processing of temperature fields.

Thus, the effectiveness of the application of the inverted-camber rim specimens combined with optical recording procedures for strain and temperature fields for studying of plastic yielding macro localization upon the compound stress state was demonstrated. The work was carried out at the Resource Sharing Center ‘Center of Experimental Mechanics’ subordinated to Perm National Research Polytechnic University, with funding from the Russian Science Foundation (no. 18-79-00242).

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