Development of a multi-cycle shear-compression testing for the modeling of severe plastic deformation

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Abstract. The mechanism of severe plastic deformation comes from very significant shear strain. Shear-compression testing of materials is complicated by the fact that a state of large equivalent strain with dominant shear strain is not easily achievable. This paper presents the novel technique of laboratory simulation of severe plastic deformation by multi-cycle shear-compression testing at room temperature with equivalent strain $e=1...5$. The specimen consisted of a parallelepiped having an inclined gauge section created by two diametrically opposed semi-circular slots which were machined at 45°. Height of the specimen was 50 mm, section dimensions were 25x25 mm, gauge thickness was 5.0 mm and gauge width was 6.0 mm. The specimen provided dominant shear strain in an inclined gauge-section. The level of shear strain and equivalent strain was controlled through adjustment of the height reduction of the specimen, load application direction and number of cycles of shear-compression.

Aluminium alloy Al-6.2Mg-0.7Mn was used as a material for specimen. FE simulation and analysis of the stress-strain state were performed. The microstructure of the specimen after multi-cycle shear-compression testing with equivalent strain $e=1...5$ was examined by optical and scanning electron microscope.

1. Introduction
Severe plastic deformation (SPD) can be used to improve the microstructure and mechanical properties of metallic materials [1]. The mechanism of SPD comes from very significant shear strain. Laboratory simulation of stress-strain state and microstructure evolution, which are similar to that occurring during SPD, is very important for design of technologies of producing ultrafine grained materials. It can allow to consider a variety of technological variants and to find the best solution in relatively short time and with low costs. Shear-compression testing of materials is complicated by the fact that a state of large equivalent strain with dominant shear strain is not easily achievable. Problem of selection of shear testing and specimen geometry has been discussed in numerous publications. A shear-tensile specimen was developed by Hundy and Green [2]. Another example of such a specimen is the so-called “hat specimen” which was developed by Meyer and Manwaring [3], and used thereafter by many other researchers. Another variant is the double shear specimen used by Klepaczko [4]. Very simple specimen geometry (thin foil) has been used by Clifton and Klopp [5] in their pressure-shear plate impact experiments. Peirs et al. [6] introduced the eccentric notch shear specimen, which was designed for shear testing of sheet metals over a wide range of strain rates. Isakov, et al. [7] used modified specimen geometry, based on ASTM B831 [8], which presents specimen geometry intended to determine the ultimate shear strength of wrought or cast aluminium alloys. The specimen geometry consists of a planar specimen with a gauge section created by two opposing 45° slots.
through the specimen thickness. This sample geometry was modified for use in a tension Kolsky bar. It was shown that the specimen without the thickness reduction exhibits severe distortion outside of the intended gauge section. A shear-compression specimen for large strain testing of materials was developed by Rittel et al. [9]. The specimen consists of a cylinder having an inclined gauge section created by two diametrically opposed rectangular slots which are machined at 45° with respect to the longitudinal axis. The specimen was used in numerous investigations, including constitutive testing, texture evolution, and adiabatic shear banding. A miniature version of the shear-compression specimen was used for the characterization of nanomaterials. The modified shear-compression specimen was presented in [10]. In the modified specimen, the two diametrically machined gauges were semi-circular (instead of rectangular). This modification induces large strains on the mid-section of the gauge without the sharp edges and stress concentrations of the former rectangular gauges. The goal of this research is a development of a novel laboratory testing method which can be used for design of technology of SPD of fine grained aluminium alloys.

2. Research method
Simulation of a multi-cycle shear-compression testing was performed by using an AG IC Shimadzu universal testing machine equipped with a 300 kN load cell. Aluminium alloy Al-6.2Mg-0.7Mn with flow stress (Fig. 1) was used as a material for specimen (Table 1). The specimen (Fig. 2) consisted of a parallelepiped having an inclined gauge section created by two diametrically opposed semi-circular slots which were machined at 45°. Height of the specimen was 50 mm, section dimensions were 25×25 mm, gauge thickness was 5.0 mm and gauge width was 6.0 mm. The circular gauge had a radius of 3.0 mm. The specimen provided dominant shear strain in an inclined gauge-section. The specimen was compressed between two flat dies during shear-compression testing in accordance to the scheme (Fig. 3). Velocity of the top die displacement was 500.0 mm/min (8.33 mm/sec) in all variants. The level of shear strain and equivalent strain was controlled through adjustment of the height reduction of the specimen, load application direction and number of cycles of shear-compression. Each cycle of the shear-compression testing consisted of two steps. The first step included 10% of height reduction of specimen, after that specimen was rotated by 90°. The second step included reduction of the width from w to 25 mm (Fig. 3) for getting the quasi original shape of a parallelepiped. One cycle of shear-compression testing provided equivalent strain ε≈1.0 in an inclined gauge-section. Multi-cycle shear-compression testing was performed at room temperature with equivalent strain up to ε≈5. Numerical simulation and analysis of the stress-strain state during shear-compression testing was performed with the commercial finite element software DEFORM 3D. The specimen was meshed with 80000…100000 tetrahedral elements during simulation. A Coulomb friction model was used between dies and specimen. The dies were assumed as rigid. The specimen was an elastic-plastic. The friction coefficient on the contact surfaces was μ = 0.08.

| Table 1. The chemical composition of the aluminum alloy Al-6.2Mg-0.7Mn. |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Si             | Fe             | Cu             | Mn             | Mg             | Zn             | Ti             | Be             | Al             | balance        |
| 0.14           | 0.25           | 0.03           | 0.73           | 6.2            | 0.08           | 0.04           | 0.0008         | balance        |

Figure 1. Stress-strain curve of Al-6.2Mg-0.7Mn. Figure 2. Specimen for shear-compression testing.
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Simulation results and discussion
The experimental shear-compression testing (Fig. 4) was computer controlled with registering the top die displacement and load. The comparison of experimental and numerical load-displacement curves during the first and the second steps of the first cycle of the shear-compression testing showed high accuracy (Fig. 5).

Asymmetry of the velocities of the metal flow is generated in gauge section during each cycle of the shear-compression testing. Asymmetry of the velocities leads to high shear strain which is localized in gauge section. It should be noted that the height reduction of the specimen is the important factor that influence on the level of strain during shear-compression testing. With increasing the height reduction to 10% the effective strain is increased up to $e \approx 1.0$. So the level of strain can be controlled through adjustment of the height reduction of the specimen during shear-compression testing. However the height reduction of the specimen is limited by its destruction. The results of the stress-strain state of metal during shear-compression testing were analyzed. Distributions of the effective stress, strain and strain rate along the mid-section of the specimen are shown in Fig. 6. The uniform distributions can clearly be observed. High level of strain ($e \approx 1.0$) is localized in gauge section and it is typical for large plastic deformation.

The microstructure in gauge section of the specimens after 1...5 cycles of the shear-compression testing was examined by optical and scanning electron microscope (Fig. 7). Significant grain refinement was observed in Al-6.2Mg-0.7Mn after 5 cycles ($e \approx 5$) of the shear-compression testing.
Figure 6. Fields of the effective strain rate (a), effective stress (b) and effective strain (c) during shear-compression testing.

Figure 7. Microstructure after one (a) (×100) and five cycles (b) (×3000) of the shear-compression testing.

4. Conclusions
A novel technique of laboratory simulation of SPD by multi-cycle shear-compression testing was presented. The specimen consisted of a parallelepiped having an inclined gauge section created by two diametrically opposed semi-circular slots which were machined at 45°. Height of the specimen was 50 mm, section dimensions were 25×25 mm, gauge thickness was 5.0 mm and gauge width was 6.0 mm. The circular gauge had a radius of 3.0 mm. The specimen provided dominant shear strain in an inclined gauge section. The level of shear strain and equivalent strain was controlled through adjustment of the height reduction of the specimen, load application direction and number of cycles of shear-compression. Aluminium alloy Al-6.2Mg-0.7Mn was used as a material for specimen. FE simulation and analysis of the stress-strain state were performed. Asymmetry of the velocities of the metal flow leads to high shear strain in gauge section of the specimen during the shear-compression testing. Uniform distributions of the effective stress and strain were shown. Significant grain refinement was observed in Al-6.2Mg-0.7Mn after 5 cycles (e=5) of the shear-compression testing. The results of investigation can be used for design of technology of producing of fine grained aluminium alloys.

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