Finite element analysis of Al-Mg alloy elasto-plastic behavior and fracture during dynamic perforation

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Abstract. A mechanical behavior of Al-Mg alloy subjected to the dynamic perforation test at different strain rates was described by numerical modelling. Deformation - fracture process was investigated. Dynamic penetration tests were carried out; stress–strain curves were obtained at different rates. Johnson-Cook material and failure models were used. Model parameters have been determined experimentally. Numerical data were compared with experimental data, obtained by penetration tests with different strain rates. Finite element results are in good agreement with the experimentally obtained results under the domain of the strain rates considered in the present study.

1. Introduction
It is well known that an aluminum energy absorption per density unit is higher compared to steel. It is the reason why aerospace industries are interested in aluminum alloys for. Concerning that, the mechanical behavior and damage accumulation prediction tasks by numerical models are interesting for study. However, a numerical modeling of constructions made of Al-Mg alloys mechanical behavior at dynamical loading conditions is problematic due to lack of data. There is a request for dynamic testing and experimental results [1-4].

2. Materials and methods
Perforation testing is one of the necessary research methods, which allows to investigate material in a wide range of deformation rates. This method for determining plasticity of sheet alloys represents biaxial tension of test specimens; the scheme is shown in Figure 1a. A finite element mesh model for the numerical experiment is shown in Figure 1b. During the testing an axially symmetric indenter with a speed of 5 to 10 m/s, punches a rigidly fixed sample of sheet material. The sample material experiences large plastic deformations before fracture.

A widely used in aerospace industry Al-Mg 1560 alloy sheet in a delivery condition was chosen as a research subject. Aluminum alloy 1560 refers to the strain hardened aluminum alloys. Rolled sheets are delivered in annealed condition. Chemical composition: Mg – 6.124 %, Mn – 0.597 %, Fe – 0.351 %, Si – 0.310 %, Zn – 0.203 %, Ti – 0.0843 %, Cu – 0.086 %, Al – mass (Russian grade 1560 alloy). Test circle specimens with 60 mm diameter and 1.5 mm thickness were cut from an initial sheet.
Figure 1. Experiment scheme (a) and grid model for calculations (b)
1 – specimen, 2 – indenter, 3, 4 – The lower and upper parts of the support matrix.

Numerical modeling complexity of such processes is the correct selection of the equation of state, strength and failure models. The high strain rate punch tests were performed in an Instron VHS 40/50-20 servohydraulic test bench for further comparison with the numerical modeling results of the deformation behavior of Al-Mg sheets under the large plastic deformations conditions. During the testing, changes of effort and displacement by time were recorded during punch tests of the 1.5 mm thick sheets. The forces dependencies up to the destruction at loading rates from 5 to 10 m/s were obtained.

The numerical task of the dynamic penetration modeling was solved by finite element method. A computational domain prepared by means of the ANSYS Workbench 15 software package is shown in Figure 1b. The numerical experiment was carried out by using the AUTODYN specialized for solving dynamic problems software. A round flat specimen rests on the lower parts support, which is rigidly fixed. A cylindrical indenter with a hemispherical end moves toward the sample at a constant speed. An indenter-sample interaction occurs before reaching the maximum permissible deformations and loads corresponding to the material destruction.

The Johnson-Cook material model was used to describe the Al-Mg alloy mechanical behavior [5]. The model considers the temperature and strain rate effect on the flow stress and the ultimate degree of material strain:

\[
\sigma = \left[ A + B\varepsilon_p^n \right] \left[ 1 + C \log \frac{\dot{\varepsilon}}{\varepsilon_0} \right] \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]
\]

where \( \varepsilon_p \) – is the effective plastic deformation, \( T_m \) – is the melting point, \( T_r \) – is the room temperature, \( A, B, C, n, m, \varepsilon \) – are the model parameters.

3. Results and discussion
After analyzing the obtained numerical data (Figure 2), it was found that in the area before the maximum load was achieved, the results obtained using the Johnson-Cook model are in close agreement with the experimental data [6-7]. There is a need to select a failure numerical model, because of the sample destruction during the experiment. Description of the sample destruction process was carried out by the Johnson-Cook failure model:
\[ D = \frac{1}{\varepsilon_f} \sum_i \Delta \varepsilon_p^i \]  

(2)

where \( \varepsilon_f \) is the material ultimate strain, \( \Delta \varepsilon_p^i \) is the element effective plastic strain increment at the i-th integration step over time.

The \( \Delta \varepsilon_p^i \) value is calculated by the formula:

\[
\Delta \varepsilon_p^i = \left( D_1 + D_2 \exp \left( D_3 \frac{p}{\sigma_{ef}} \right) \right) \left( 1 + D_4 \ln \frac{\varepsilon_f}{\varepsilon_0} \right) \left( 1 + D_5 \frac{T - T_c}{T_m - T_c} \right)
\]  

(3)

where \( D_1, ..., D_5 \) are the material parameters, \( \sigma_{ef} \) is the effective stress, \( p \) is the considered element pressure. According to the selected criterion, the final element destruction occurs if the damage parameter \( D = 1 \).

Constants values for the material and fracture models were determined experimentally. The experimental data were obtained earlier during tensile tests on flat specimens from the same material. Experimental data and numerical data obtained using the J-C deformation model and the J-C fracture model show qualitative and quantitative agreement throughout the all deformation region (Figure 3). This suggests the correct choice of the determining equation, the failure model, the models constants and the mesh density.

An erosion model was used to visualize the destruction process. The erosion model operation principle was as follows: the element was automatically excluded from the solution when the element's damage parameter \( D \) reached a value of 1, however, it continued to be present in the grid model, creating the illusion of integrity. When the erosion model was turned on, the elements in which the fracture criterion was achieved were removed. Thus, the erosion model inclusion to the calculation in conjunction with the Johnson – Cook failure model made it possible to obtain a fracture image as close to reality as possible.
Figure 3. Time dependence of the deforming force during the experimental test of the sample (black dotted line) and the J-C material + J-C failure model simulation at loading speeds of 5 and 10 m/s (red line).

The numerical simulation results quality was estimated by comparing experimental and numerical results of the high strain rate punch tests at different strain rates. A good qualitative and quantitative agreement was obtained. The obtained results can be used in designing technological processes of sheet materials dynamic pressing, as well as in estimating strength and durability of constructions made of 1560 alloy under dynamic effects.

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