Abstract: Microscopic phenomena of the tensile deformation of the multi-phase metal-matrix materials, and of the matrix material flow in situ are very difficult to be traced. The solution of that problem is presented by macroscopic models enlarged for few orders of magnitude in comparison to the microstructure of real engineering materials. These models are suitable for the experimental as well as for the finite element analysis. The mechanical properties of single model components are relatively very well comparable to those of the true multi-phase metal-matrix materials.

Key words: multi-phase metal-matrix material, tensile deformation, modelling, testing

1. INTRODUCTION

Important progress has been made in recent years in the scientific field of micro and macromechanical modelling of elastic and plastic deformation of multi-phase materials [1-3].

Phenomena of deformation and destruction of multi-phase metal-matrix materials are two of the most interesting problems in the scientific field of material science [4,5]. These two problems are very important because of the mechanical and applicable properties of the two-phase metal-matrix materials, such as their behaviour among the processes and treatments with different types of the mechanical engineering technologies [6]. With the tools of material science and physical metallurgy it is impossible to detect the processes in material on the macroscopic level [7]. That was the main reason that we tried to describe the processes in multi-phase metal-matrix materials among the plastic deformation due to the tensile loading with macroscopic models, destructive and non-destructive material testing methods, and numerical modelling (Fig. 1).

The constituents which presented metal matrix and secondary-phase particles (inclusions) are enlarged for few orders of magnitude in comparison to the real multi-phase metal-matrix materials. With the adequately combination of materials, geometries and arrangement of the constituents in the model, with corresponding non-destructive testing methods which enable observation of the model after the separate stages of deformation, with microhardness measurements, and the finite element analysis (FEA), the picture about sequences of the process at the tensile loading of multi-phase metal-matrix materials has been obtained [8].
2. EXPERIMENTAL WORK

For the transformation and enlargement of the phenomena in the microstructure into the macroscopic world the macroscopic models considering tensile deformation have been done.

The models were composed of the metal tube and cylindrical inserts. In this types of models the matrix were simulated with the wall of the tube, and cylindrical inserts represented secondary-phase inclusions. This model enables direct observation of the matrix (tube) deformation; especially in zones directly at the inserts [9]. Tubes were made of ductile metals and alloys (copper, aluminium and their alloys), which were adequately heat treated (with annealing and quenching). Inserts were made of much more rigid materials (low-carbon and tool steels) [10].

The tensile tests have been done on the universal static-dynamic testing machine INSTRON 1255 (Fig. 2). The composed macroscopic models have been loaded up to the maximal tensile load at the tensile test. Before and after deformation with the tensile test, the macroscopic models have been investigated by X-ray diffraction, and by γ and neutron radiography (Fig. 3).

3. FINITE ELEMENT ANALYSIS

Numerical modelling of the tensile loading process of the macroscopic models of two-phase metal matrix materials have been done with finite element method (FEM), by ABAQUS software [11].

Input data for the finite element analysis (FEA) includes informations about: initial geometry of the system, mechanical properties of the individual constituents, initial, boundary and interface conditions and loads [12,13]. At the model description is also very important data the definition of the contact properties (friction) between matrix and secondary-phases inclusions. The axial symmetry of the tensile deformed systems matrix - inclusion (uniform or composed) has been considered.

<table>
<thead>
<tr>
<th>Model</th>
<th>Matrix</th>
<th>Inclusion</th>
<th>( L_1 ) (mm)</th>
<th>( D_{1/2} ) (mm)</th>
<th>( D_{2/2} ) (mm)</th>
<th>( l_f ) (mm)</th>
<th>( l_p ) (mm)</th>
<th>( AL ) (mm)</th>
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</thead>
<tbody>
<tr>
<td>I</td>
<td>Cu</td>
<td>Steel</td>
<td>160.0</td>
<td>10.0</td>
<td>8.0</td>
<td>26.8</td>
<td>8.1</td>
<td>40.0</td>
</tr>
<tr>
<td>II</td>
<td>Cu</td>
<td>Steel</td>
<td>160.0</td>
<td>10.0</td>
<td>8.0</td>
<td>11.8</td>
<td>9.1</td>
<td>20.0</td>
</tr>
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</table>

Fig. 4 Model - Initial geometry parameters of the experimental models I (left) and II (right) used in the finite element analysis.
The initial geometry parameters of the experimentally achieved macroscopic models have been used for description of the initial geometry in FEA. The initial parameters of the model I are the initial parameters of the experimental achieved model of the system matrix (tube) - uniform cylindrical inclusion, and the model II represents the experimental achieved model of the system matrix - composed cylindrical inclusion. All experimental models, used for FEA, have been composed in the way that the inserts have been put directly in the middle part of the matrix. Because of double symmetry of the chosen macroscopic models, owing to the tensile and radial axis it was possible in FEA to use only one quarter of the experimentally simulated macroscopic model (Fig 4).

Mechanical properties of the testing materials have been used on the base of the unaxial tensile tests or have been assumed on the base of the data from the professional literature [14]. For the matrix of the numerical simulated models, the copper tubes have been chosen. The value of the Young’s modulus of the copper matrix is 119.0 GPa, and the Poisson’s ratio is equal 0.343. True stress - true strain curve of the matrix (copper tube) was described by Holomon’s expression:

\[ \sigma = K \cdot \varepsilon^n \]  

(1)

where:
- \(\sigma\) is true stress,
- \(K\) is stress constant,
- \(\varepsilon\) is true strain, and
- \(n\) is strain-hardening exponent.

The value of the stress constant is 320 MPa, and the strain hardening coefficient is equal 0.54.

Matrices of the numerical simulated models have been modelled with the finite elements type CAX4, interfaces with type IRS21A, and the inclusions were simulated as a perfect rigid bodies [15].

Friction coefficient on the inclusion - matrix interface was assumed as an constant value (\(\mu = 0.1\)) [16]. With the different model parameters (geometry, mechanical properties of the components, initial, boundary and interface conditions and loads) the numerical simulations have been done repeatedly. On this place only Von Mises equivalent stress in the matrix of the basic experimentally simulated models I and II is present (Fig 3).

The Von Mises equivalent stress is defined with the principal stresses as follows:

\[ \sigma_m = \frac{1}{2} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \]  

(2)

with:
- \(\sigma_1\) as radial stress,
- \(\sigma_2\) as axial stress,
- \(\sigma_3\) as tangential stress, and
- \(\sigma_m\) as Von Mises equivalent stress.

In Figures 5 and 6 is present Von Mises equivalent stress distribution in matrices of the model I at 25 % deformation, and at the model II at 12.5 % deformation.
4. CONCLUSIONS

The aim of our study is the designing of a corresponding macroscopic model of the multi-phase metal - matrix material useful for the tensile deformation tests, which should be suitable for both: experimental and numerical simulation and analysis. The basic aim of the connected experimental - numerical analysis is in the observation of the matrix material flow, and in the description of the stress - strain state in the matrix.

The changes of the geometrical parameters of the tensile deformed macroscopic models have been observed in situ with the transmission of macroscopic models with the X-rays, γ-rays and neutrons. For computational modelling the FEA and the ABAQUS software have been employed. The outcome of the FEA explains the results of the experimental investigations.

This investigation shows that it is possible to observe the phenomenon of elastic and plastic deformation of multi-phase metal-matrix materials on the macroscopic models composed of elements, which have properties very similar to the constituents of the real materials. The composed models should be in praxis useful for the tensile loaded multi-phase metal-matrix materials and composites.

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