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Macroscopic modelling and simulation of two-phase copper matrix materials subjected to tensile deformation

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Analysis and modelling

ABSTRACT

Purpose: Phenomena of deformation and fracture of two-phase metal matrix materials are two very interesting problems in the sceintific field of materials science and engineering. The study of these two issues can greatly contribute to better mechanical and technological properties of two-phase metal matrix materials.

Design/methodology/approach: This work presents macroscopic models of two-phase metal matrix material, composed of ductile matrix and more rigid and hard inclusions (inserts) of secondary phase, prepared for the tensile deformation. These types of models are enlarged for two to three orders of magnitude comparing to the real copper matrix materials, and they are suitable for numerical as well as experimental modelling and simulation.

Findings: The basic aim of the numerical and experimental modelling is in the observation of the matrix material flow, and in analysis of the stress-strain state in the matrix.

Research limitations/implications: Deficiencies in FEA of the tensile deformation process of represented models, are suppositions: that in the models a non-stressed initial state were supposed, that the secondary-phase inclusions and particles were simulated as perfect rigid bodies, and that the Coulumb coefficient of friction on the insert-matrix interface was assumed as a constant value.

Practical implications: The changes of geometrical parameters of the tensile deformed macroscopic models have been experimentally observed with the hardness measurements, geometry measurements, image analysis, and non-destructive testing methods.

Originality/value: The most important results of that macroscopic simulation is in the observation of the material flow, the formation and propagation of cracks, motion of the broken secondary-phase inclusions and particles in the matrix, and the stress-strain analysis.

Keywords: Analysis and modelling; Computational materials Science and mechanics; Composites; Macroscopic modelling; Finite Element Analysis (FEA)

1. Introduction

Important progress has been made in recent years in the field of modelling of complex materials [1, 2]. The deformation and fracture of two-phase metal matrix materials [3] are two of the most interesting and important problems in the materials science and engineering. The study of these two issues can greatly contribute to better mechanical and technological properties of two-phase metal matrix materials [4, 5].

The deformation behaviour of material during its production using different metallurgical and mechanical engineering technologies is such an example (Fig. 1). Physical metallurgy and materials science discuss this problem, but it is difficult to follow the processes in the material on the microscopic level [6].

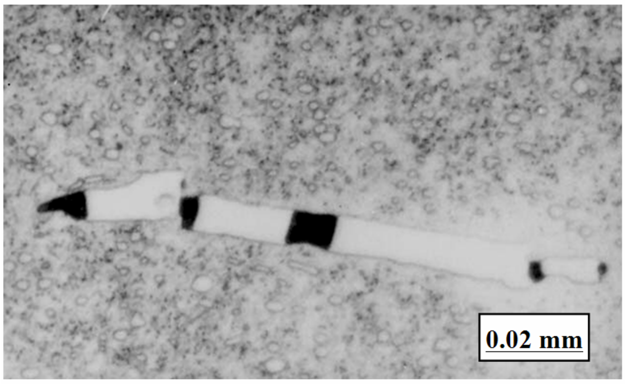


Fig. 1. Microstructure of the hot tensile deformed chromium ledeburitic tool steel

This is the main reason that in the frame of our study the processes in two-phase metal matrix materials during plastic deformation due to tensile loading have been described with macroscopic models. The components presenting secondary-phase particles, inclusions and other microstructure parameters are magnified by a few orders of magnitude (100 to 1000 times), comparing to the real two-phase metal matrix materials [7,8]. With corresponding non-destructive testing methods (NDT) which enable observation inside, throughout the whole volume of the model after each step of deformation, with the support of hardness measurements, image analysis and finite element analysis (FEA), it is possible to get a better picture about the what is going on in the process at the tensile loading of two-phase metal matrix materials (Fig. 2) [9].

2. Experimental work

For the transformation and magnification of the microstructure phenomena into macroscopic dimensions the models for observing tensile deformation have been done [10]. The models were composed of metal tube (matrix) and cylindrical metal inserts. Matrices were made from ductile metal (technical pure copper) which was adequately heat treated (with annealing and water quenching) to reach the maximal ductility [11,12]. But cylindrical low carbon steel (with approx. 0.2 % C) inserts were normalized, and they consisted of one or of three parts of different lengths. Composed cylindrical inserts were with spherical front and end faces, and with flat internal boundary surfaces, as found with fragments of fractured inclusions in real materials [13]. The models were made so that the inserts had been inserted in the middle part of the tube. This type of models enable direct observation of the tube (matrix) deformation; especially in the zones in contact with the inserts.

The tensile tests were carried out on the universal static-dynamic testing machine INSTRON 1255 (Fig. 3). All experiments were done at the ambient temperature.

The elongation of the copper tube (ΔL) and tensile load (F) were automatically measured parameters. Before and after deformation the macroscopic models were investigated by X-ray, gamma and neutron radiography [14] (Fig. 4.)

An especially good macroscopic picture about the occurrences in the individual characteristic points of the model can be obtained from the measurements of the local deformation with the support of the measurement of the tube wall thickness and the deformation hardening microhardness measurements. In our early published investigation work [15] is presented the deformation hardening zone in the copper tube. The magnitude of local deformation was obtained from deformation - deformation hardening relationship.

In the scope of experimental work hardness measurements on the tube made from technical pure copper, with uniformed or

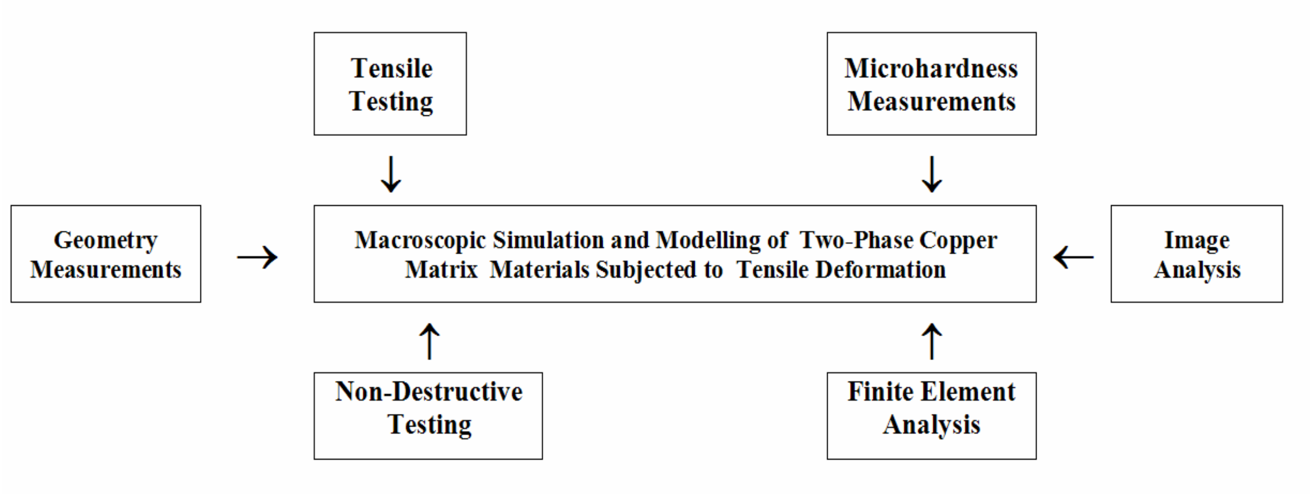


Fig. 2. Investigation concept

particulated inserts have been carried out. The external dimensions of the model, before and after tensile deformation, have been measured with an accuracy of ± 10 µm. The changes of the wall thickness (with an accuracy of ± 5 µm) and hardness across the wall thickness have been measured on the typical radial and longitudinal tube cross-sections (Figs. 5 and 6). The hardness has been measured in Vicker's (HV1, HV2) in direction from the inner to external tube wall.

The inserts were made of low carbon steel, and their deformation was negligible in correspondence to tube deformation. So the hardness changes of steel inserts were limitting towards to zero.

Fig. 3. Universal static-dynamic testing machine INSTRON 1255

3. Finite element analysis

Numerical computations were carried out on PC computer using the commercial multi-suppose finite element program ABAQUS [16].

Input data for the finite element analysis (FEA) include information about [15-17]:

- initial geometry of the macroscopic model (tube – insert),
- mechanical properties of the individual constituents,
- contact properties (friction coefficient) on tube - insert interface, and
- external tensile load.

The initial geometry parameters of the experimentally achieved macroscopic models have been used for description of the initial geometry in the numerical calculations. The initial parameters of the models (Fig. 7) are the initial parameters of the experimentally achieved models of the system copper tube (matrix) and uniform (model I) or composed (model II) cylindrical insert made from low carbon steel.

Experimental model used in numerical analysis were composed so that the insert or composed inserts have been put directly in the middle part of the matrix. In both cases the geometry was axisymmetric, and the deformation was assumed to be axisymmetric, too.

Because of the double symmetry of the chosen models, owing to the tensile z (2) and radial axis r (1), it was possible to use, in the FEA, only one quarter (1/4) of the experimentally simulated macroscopic model (Fig. 7).

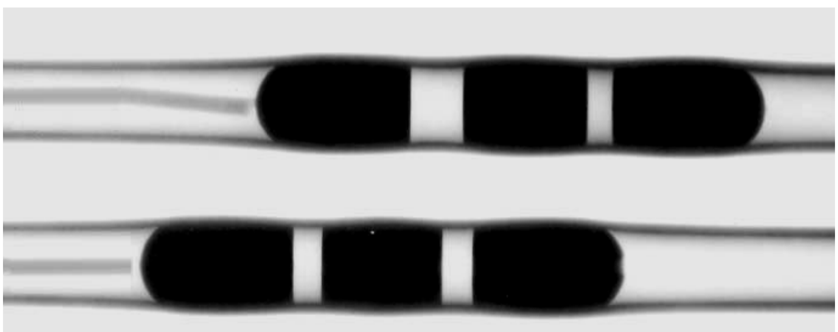
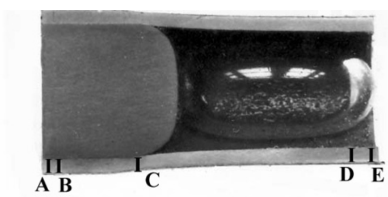


Fig. 4. Tensile deformed tubes made by copper. Loading of tubes is up to the maximal tensile load. Separation of the assembled inserts; deformation of the tube wall. Radiography. Magn. approx. 2 x



Measuring Point	A	B	C	D	E
Distance Between Measuring Points (mm)	0.0	0.6	4.6	11.3	1.9
Wall Thickness (µm)	840	840	660	800	805

Fig 5. Copper tube with the insert from low carbon steel deformed up to the maximal tensile load. Magn. approx. 4 x. In the table are values of the tube wall thickness in the characteristic measuring points

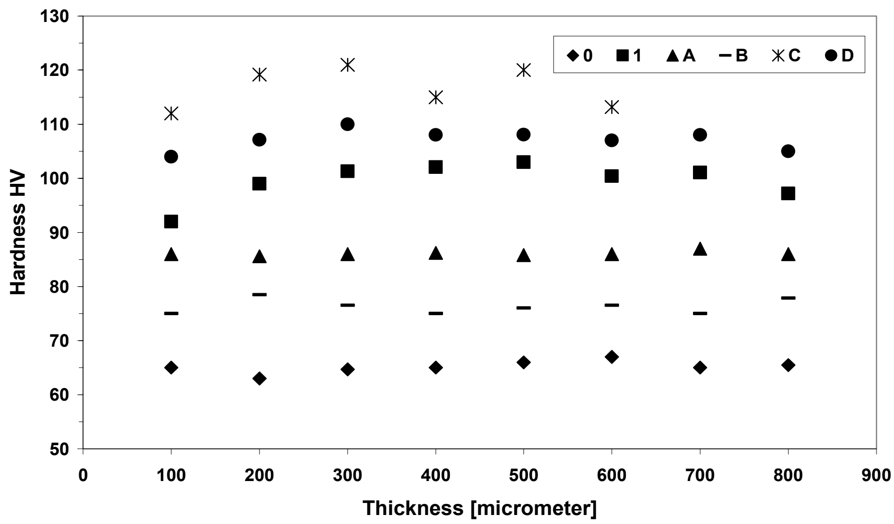


Fig. 6. Microhardness measured on the model (Fig. 5) in the characteristic points. 0 – empty tube (nondeformed); 1 – empty tube (deformed); A – point A; B – point B; C- point C; D – point D

Model	Matrix	Inclusion	L_0 (mm)	D_{0z} (mm)	D_{0n} (mm)	l (l_1) (mm)	l_2 (mm)	ΔL (mm)
I	Cu	Steel	160.0	10.0	8.0	26.6		40.0
II	Cu	Steel	160.0	10.0	8.0	18.1	9.1	20.0

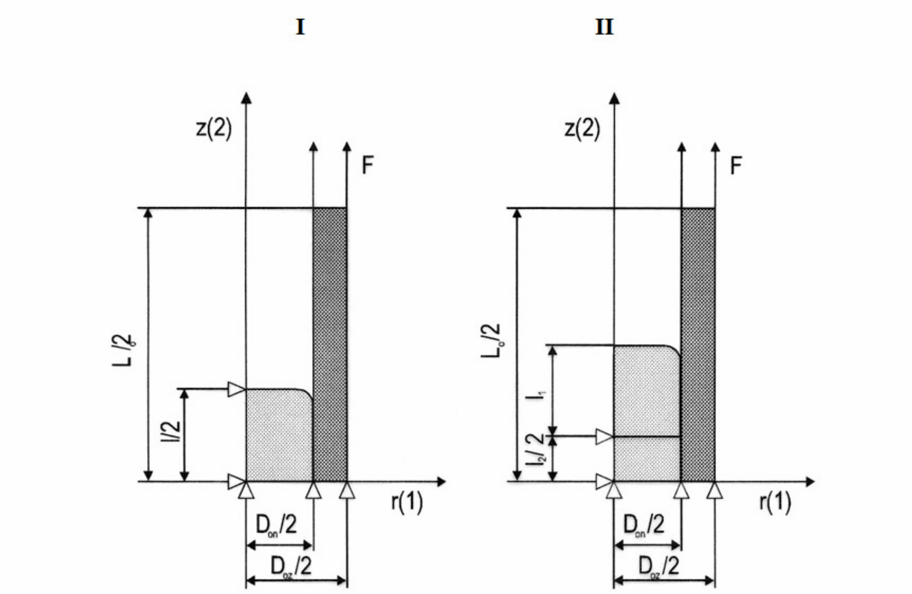


Fig. 7. Initial geometry parameters of the experimental models I and II used in the finite element analysis

On the top of the analysed copper tube (matrix) the value of displacement is described with the tensile deformation and on symmetry axis r (at z = 0) it is equal zero (fixed support). The displacements in radial direction are free, only on the border with the insert(s) they are limited with its (their) geometry. Double symmetry dictates that the top and bottom surfaces of the analysed region remain planar after deformation. In the FEA initial unstressed state was taken as a reference. The deformable copper tubes (matrices) were modeled with the 4-node bilinear axisymmetric finite elements type CAX4 and cylindrical low carbon steel inserts were simulated as perfect rigid bodies. The interaction between a deformable finite element mesh of ductile metal matrix and rigid insert was modeled with axisymmetric interface finite elements type IRS21A. Coulomb coefficient of friction on the insert - matrix interface [18] was assumed as 0.1 (constant value).

The knowledge of properties describing the mechanical behaviour of the copper [19] tube was also required for the finite element analysis. Mechanical properties of the copper tube (at ambient temperature) have been defined on the basis of the unaxial tensile tests on the universal static-dynamic testing machine INSTRON 1255. The values of the Young's modulus and Poisson's ratio of the technical pure copper were 119.0 GPa and 0.343, and the uniaxial true stress - true strain curve of the tube was described by polynomial equation of the third order:

$$\sigma(\varepsilon) = 1330.88 \cdot \varepsilon^3 - 2285.49 \cdot \varepsilon^2 + 1468.39 \cdot \varepsilon + 51.33 \quad (1)$$

where:
σ (MPa) is true stress, and
ε (-) is true strain.

Below only a few of the finite element analysis (FEA) results are presented: tensile deformation geometry, and distribution of Von Mises equivalent stress and equivalent plastic strain of an experimentally simulated models I and II (Fig. 7).

In Fig. 8 we can see deformed finite element mesh (geometry), and plots of Von Mises equivalent stress and equivalent plastic strain in the matrix of model I at a deformation of 25.0 %. The basic purpose of this macroscopic simulation is to present material flow of the matrix at uniformed insert.

In the tube at the inclusions they are minimal stresses and strains. That mean that the inclusions restrain the tubes (matrix) deformation. With increasing of the inclusions aspect ratio (length / diameter) its dependence on the restrain of the matrix deformation increases. Deformation and stress concentration increasing considerably at the points of the last contact between inclusion and tube.

In Fig. 9 we can see deformed model, and plots of Von Mises equivalent stress and equivalent plastic strain in the matrix of model II at a deformation of 12.5 %. The basic purpose of that macroscopic simulation is to present material flow of the matrix at separation of the composed insert. This phenomenon represents the motion of the broken particle or inclusion under the influence of the external tensile load.

At the beginning of the tensile test the parts of the composed insert were put together very closely (in direct contact). Under the influence of the external tensile load, the parts of composed insert were moved in the direction of the external load. This led up to the phenomenon of voids between the parts of composed cylindrical insert, and in the next stage of deformation the voids began to fill up with the ductile matrix material.

Both represented models have been carried out with an optimal type and number of finite elements. Deficiencies in finite element analysis of the tensile deformation process of represented models, are suppositions that in the models a non-stressed initial state were supposed, and that the secondary-phase inclusions and particles were simulated as perfect rigid bodies.

4. Conclusions

The basic idea of presented investigation work was to design macroscopic model of the two-phase copper matrix material, useful for the tensile deformation tests, which should be suitable for experimental and numerical simulation and analysis.

The changes of geometrical parameters of the tensile deformed macroscopic models have been experimentally observed with the hardness measurements, geometry measurements, image analysis, and non-destructive testing methods.

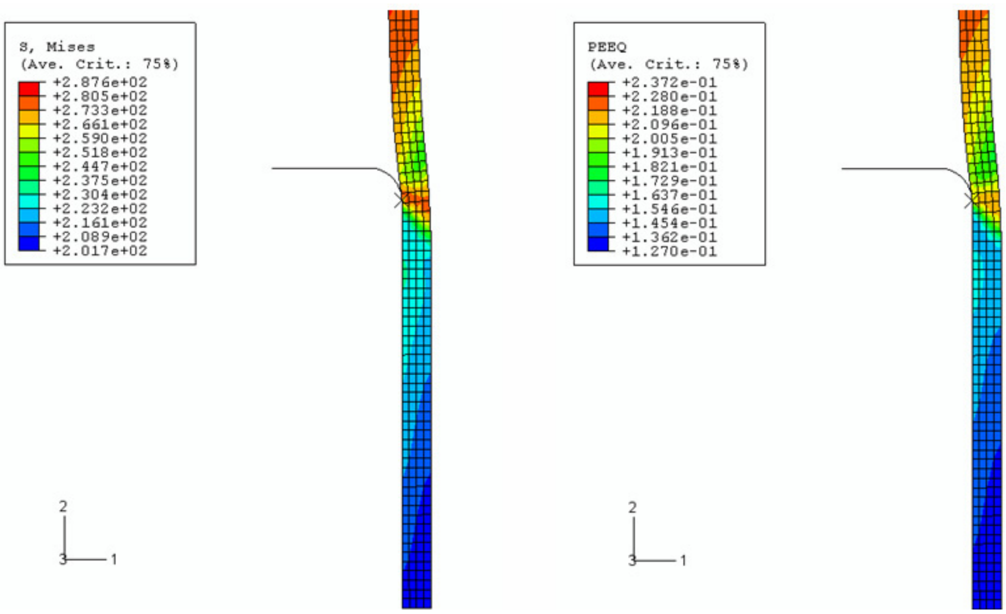


Fig. 8. Von Mises (MISES (MPa)) equivalent stress (left), and equivalent plastic strain (PEEQ (-)) (right) in the matrix of the tensile deformed model I at 25.0 % deformation

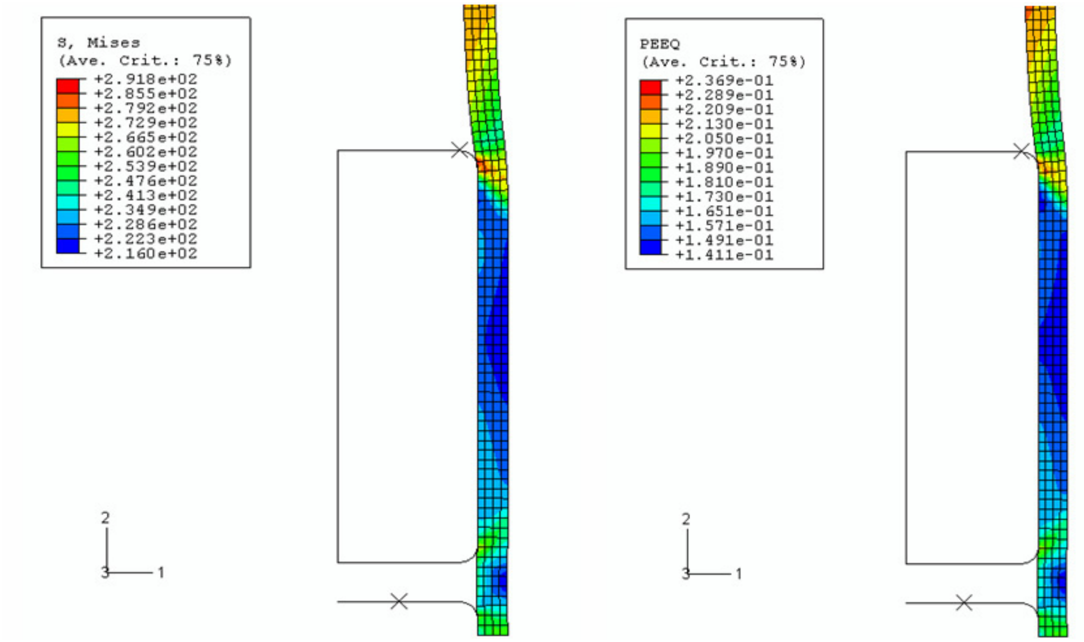


Fig. 9. Von Mises (MISES (MPa)) equivalent stress (left), and equivalent plastic strain (PEEQ (-)) (right) in the matrix of the tensile deformed model II at 12.5 % deformation

An adequate finite element model for the macroscopic simulation of two-phase copper matrix materials subjected to the tensile deformation involves combined modelling of matrix, inclusion(s) and matrix/inclusion interface.

The most important results of that macroscopic simulation is in the observation of the material flow, the formation and propagation of cracks, motion of the broken secondary-phase inclusions and particles in the matrix, and the stress-strain analysis.

Our investigation shows that it is possible to observe the phenomenon of plastic deformation of two-phase metal matrix materials on the macroscopic models composed of elements which have mechanical properties very similar to the macroscopic components of the real materials.

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