Validation of numerical model by means of digital image correlation and thermography

Ivica Skozrita, Joško Frančeski, Zdenko Tonković, Martin Surjak, Lovre Krstulović-Opara, Matej Vesnjak, Janoš Kodvanja, Bojan Gunjević, Damir Lončarica

Abstract

This paper presents experimental and numerical investigation of elasto-plastic-damage behaviour of aluminium alloys. The experimental procedure includes static and dynamic tensile tests at different strain rates as well as three point bending tests. Numerical modelling of deformation and failure process of the flat specimens is conducted by using non-isothermal elastoplastic damage constitutive model and two-dimensional plane stress finite elements. During the experiment the displacement and temperature distribution on the specimen’s surface is measured by digital image correlation (DIC) method and infrared thermography (IR). This has enabled more precise calibration of material parameters in constitutive relations.

Keywords: experiment; digital image correlation (DIC); aluminium alloy; thermography; finite element method; thermoplasticity

1. Introduction

New demands on reliability and safety, together with the applications of new materials and new production technologies, can only be realized by methods of advanced structural analysis and more realistic description of material behavior. Material plasticity and damage modeling is the basis of the integrity estimation, design and optimization procedures of structural elements. As with most other problems, the numerical simulations are increasingly replacing or complementing more expensive experiments. Application of the finite element method enables simulation of the deformation process of material up to complete fracture of structural component.

On the other hand, numerical simulations are as powerful as the physical and mathematical models behind them. Material model description, defined by constitutive relations as well as validity of the algorithm for solving constitutive equations at the integration point level, have significant influence on accuracy of numerical methods [1]. Detecting material deformation, plastic yielding and damage processes in material was always of great importance in experimental mechanics. For the precise
determination of material parameters in constitutive models, the goal of the research presented in this paper is to perform an algorithm that allows a direct comparison of numerical results with experimental measurements. Here, the experimental results are obtained by optical measuring system ARAMIS 4M [2] (from GOM mbH) what enabled us to analyse the displacements and strains on the whole specimen surface [3]. This enables the derivation of new original and efficient numerical algorithms for modelling complex deformation processes of engineering materials, with which numerical simulation is brought closer to the real behaviour of structural components. Besides, the thermoelastic stress analysis (TSA) is used as a full field method providing stress distribution of elastically cyclic loaded specimen. In our previous work we have several times applied thermal imaging, based on fast cooled infrared (IR) camera, for tracing plastified zones in metals and metal foams [4-6]. In order to be more confident with our approaches in evaluation of plastic yielding, the IR method has been compared with the digital image correlation method. Both methods have been compared based on tensile tests, proving that IR thermography can be used as a full field method applicable for evaluating plastification processes in materials.

The paper is organized as follows. Section 2 contains a description of the experimental investigations. In Section 3, the numerical formulation is described. The detailed quantitative comparisons of the experimental and numerical results are summarized in Section 4. Finally, some concluding remarks are given in the last section.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| $c$    | specific heat capacity |
| $E$    | Young’s modulus |
| $\alpha$ | coefficient of thermal expansion |
| $\lambda$ | thermal conductivity |
| $\mu$  | friction coefficient |
| $\gamma$ | Poisson's ratio |
| $\rho$  | density |
| $\sigma_{0.2}$ | yield stress |
| $\sigma_M$ | tensile strength |

### 2. Experiments

The two different aluminum alloys are investigated in this study. The flat specimens, whose geometry is illustrated in Fig. 1.(a) made from aluminium alloy Al2024-T3 are used in tensile tests. Chemical composition of alloy Al2024-T3 is as follows: 0.1Cr, 3.8Cu, 0.5Fe, 1.2Mg, 0.3Mn, 0.5Si, 0.15Ti and 0.15Zn. The tensile tests are conducted at the three different cross-head separation rates: 0.0125 mm/s, 1 mm/s and 10 mm/s. The specimens illustrated in Fig. 1.(b), used in three point bending test, are made from aluminium alloy AlCu5BiPB-T8 which has following chemical composition: 0.4Si, 5Cu, 0.7Fe, 0.4Pb, 0.4Bi and 0.3Zn. The tensile stress-strain curves are shown in Fig. 2. For quasi static tensile test mechanical characteristics of aluminium alloy Al2024-T3 are as follows: yield stress $\sigma_{0.2} = 385.9$ MPa, tensile strength $\sigma_M = 493$ MPa, Young’s modulus $E = 72.56$ GPa, Poisson's ratio $\gamma = 0.33$ and density $\rho = 2780$ kg/m$^3$. Thermal properties of material necessary for numerical simulation are taken from [7]: coefficient of thermal expansion $\alpha = 23.2$ $\mu m/K$, specific heat capacity $c = 875$ J/(kgK) and thermal conductivity $\lambda = 121$ W/(mK). In addition, the mechanical properties of alloy AlCu5BiPB-T8 are taken from [8]: $\sigma_{0.2} = 305$ MPa, $\sigma_M = 400$ MPa, $E = 76.7$ GPa and $\gamma = 0.3$.

Fig. 1. Specimen geometry: (a) tensile test flat specimen; (b) three point bending test specimen.
As mentioned before, in the presented experimental investigation, the displacements on the specimen’s surface are measured by using the noncontact digital image correlation system ARAMIS 4M. The ARAMIS system calculates the surface strains from the measured displacements, a process which in our experiments is synchronized with the thermographic measuring to find correlations between the displacement and strain of certain points on the specimen and the temperature. For this purpose, digital camera is used which is calibrated prior to measuring. Before the start of the experiment, the specimen is prepared by applying a random spray pattern over the mat surface to clearly allocate the pixels in the camera images. To obtain a good-quality raster, the mixture of titanium oxide and alcohol compressed to 1 bar is applied on the plate surface with powder spray. After recording the series of images, the optical system ARAMIS detects the displacements of the specimen through the images by means of various square or rectangular facets. From each valid facet, a measuring point is produced after the computation.

Experimental results for distribution of axial displacements for tensile test specimen and deflection of the three point bend testing specimen, measured using optical measurement system ARAMIS 4M, are shown on Fig. 3.(a) and 3.(b). Results of tensile deformation of specimen for deformation speed of 10 mm/s, measured using digital image correlation method (ARAMIS) and infrared thermography are shown in Fig. 4. At the beginning of loading both curves presented in Fig. 4 show thermal drop, what corresponds to thermoelastic cooling of elastically loaded specimen in tension, thus are reversible part of loading. Heating after cooling period is irreversible plastification where change in thermal gradient corresponds to moment of formation of tangential slip planes. Sudden drop in temperature after the failure is caused by the elastic relaxation of ruptured specimen.

Comparing results of surface temperature distribution with von Mises strain, correlation is visible. This enables detailed analysis of the von Mises strain and increase of the surface temperature correlation for dynamically loaded structural elements, from the beginning of the deformation process up to complete failure of element. Both methods show fluctuation of plastic yielding zone where yielding starts at the upper portion of the specimen. The yielding zone then moves downwards and finally localizes at the lower portion of the specimen. Final phase is characterized by the fluctuation of the 45° tangential sliding planes, until failure occurs. Both methods have been compared for loading velocities of 0.05, 0.1, and 1 mm/s, showing good agreement of located plastic zones. This experiment proves that generated heat correlates with inducted plastic strain.
Fig. 3. Experimentally measured displacement distribution: (a) tensile test (axial displacement); (b) three point bending test (deflection).
3. Numerical formulation

In authors’ previous paper [1], the computational strategy for modelling of adiabatic nonisothermal elastoplastic deformation process, employing a rather realistic material model with highly nonlinear isotropic and kinematic hardening responses, has been presented. Here, the von Mises-type yield condition expressed in space of stress and temperature, with the assumption of small strain and associativity of the flow rule, has been adopted. Shown constitutive model is analogue to the model implemented in software package ABAQUS/Standard [10]. This constitutive model is used for describing the deformation process of aluminium alloys Al2024-T3 and AlCu5BiPb-T8. Tensile test specimen and three point bending test specimen are discretized using 4 noded quadrilateral finite elements for plane stress state (Fig. 5). For three point bending test, it was necessary to model contact between surfaces of rollers and specimen using contact surfaces. Boundary conditions for displacement and force are controlled only on the rollers, which are modelled as rigid bodies. Penalty method with friction coefficient of $\mu = 0.1$ is used to solve contact problems. For three point bending test force was applied with known value, one used during the experimental testing, while the force used to simulate tensile test was taken at failure value for the specimen, as specimens were tested for failure. Fig. 6.(a) and 6.(b) show the results of numerical simulation for axial displacement for the tensile test and deflection for the three point bending test. Temperature distribution results on surface of the specimen for numerical simulation of tensile test at deformation speeds of 1 mm/s and 10 mm/s are show in Fig. 7.(a) and 7.(b).
Fig. 6. Numerically calculated displacements, mm: (a) tensile test (axial displacement), (b) three point bending test (deflection).

Fig. 7. Temperature distribution on specimen surface, °C: (a) 1 mm/s; (b) 10 mm/s.

4. Experimental and numerical results comparison

Fig. 8.(a) shows the distance deviation between numerically modelled geometry of the specimen for tensile testing mapped onto the geometry of the specimen measured using digital image correlation method by use of manual and best fit registration methods. Due to imperfect geometry mapping there exist local deviations between data that affect the accuracy of the true deviation of results. The axial displacement deviations between numerical simulation and experimental data are shown in Fig. 8.(b). Analogue, for three point bending test, Fig. 9.(a) shows the mapped geometry, and in Fig. 9.(b) deflection deviations are given. For three points bending test, greatest deviation between results is in the areas of contact of rollers and specimen because of large plastic deformation due to stress concentration in those areas. Three point bending test shows better agreement of data than tensile test, with regard that for three point bending test exact value of force applied was known in simulation, while for tensile test force value was not known exactly, but was taken for failure scenario, and may deviate from force used for represented stress case in Fig 3.(a), which leads to greater deviations of results than expected for known exact applied force value. Fig. 10.(a) and 10.(b) show maximum (red line) and minimum (blue line) temperature change during deformation time on the specimen surface for deformation speed of 1 mm/s. Experimental data are measured dependent of frame per second (fps) characteristic of the thermal camera, which is 600 fps, while the numerical data are given in dependence of the load increment. Here, load time increment does not represent real time, which leads to differences in the diagrams [9]. Also, the experimental results show temperature changes both in the elastic and plastic deformation range, while the numerical constitutive model neglects the thermo-elastic effect. Numerical data should be compared with the maximum (red line) temperature change data. Fig. 11.(a) and 11.(b) show maximum (red line) and minimum (blue line) temperature change during deformation time on the specimen surface for deformation speed of 10 mm/s. As may be seen, the numerical model predictions are found to be in good agreement with the real experimental data.
Fig. 8. (a) Local geometry deviation, mm; (b) axial displacement deviation, mm.

Fig. 9. (a) Local geometry deviation, mm; (b) deflection deviation, mm.
Fig. 10. Results of temperature change for 1 mm/s, °C: (a) experimental; (b) numerical.
5. Conclusion

In this paper algorithm for direct comparison of numerical and experimental data for displacement on the entire discretized surface has been developed. Elastoplastic deformations measured with ARAMIS 4M system have been brought in correlation with change in surface temperatures measured with middle wave cooled infrared thermo camera. Comparison of numerical and experimental displacement data has been conducted using user created python script. Efficiency and accuracy of the developed algorithm for validation of numerical model has been shown on examples of static and dynamic tensile test of aluminium alloy Al2024-T3 and on example of three point bending test of aluminium alloy AlCu5BiPb-T8.

It has been shown that IR thermography can be used as a robust method for evaluating plasticity in dynamically loaded specimens. Comparison of IR thermography with the digital image correlation method ARAMIS proved that generated heat represents the plastic strain in material. Both methods proved to be applicable for evaluation of dynamic loading processes.

Developed algorithm for direct comparison of numerical and experimental data for displacement on the entire discretized surface is hopeful also for applications on cyclic plasticity.

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