Experimental analysis of energy conversion during deformation process based on coupled DIC and IRT results

Sandra Musiał[1a], Michał Maj[1], Leszek Urbański[1] and Marcin Nowak[1]

[1]Institute of Fundamental Technological Research Polish Academy of Sciences

ul. Pawińskiego 5B, 02-106 Warsaw, Poland

[a]smusial@ippt.pan.pl

Introduction

The aim of the paper is to propose a new experimental approach to obtain the components of the energy balance during deformation of the material. Similarly to some works present in the literature, the developed methodology is based on the simultaneous measurements of the displacement and temperature fields using digital image correlation (DIC) and infrared thermography (IRT) techniques. Nevertheless, some important aspects of the determination of heat sources are original and not yet present in the literature. Moreover, in this research, contrary to the results present in the literature, the experimental field analysis of all components of energy balance will be performed and time evolution of these fields will be presented. Additionally, the influence of the strain rate and in consequence the process duration, on the heat sources will be studied.

Methodology

The field analysis of the energy conversion during plastic deformation consists of the determination of both the plastic work and the energy dissipated as heat distributions. As for the first, the method of the DIC-based stress field determination has been already developed by the authors [1]. In the present study, the constitutive model has been extended of the influence of strain rate and plastic anisotropy. The plastic anisotropy is described by the yield function introduced by Barlat and Liam [2]. Additionally, in our approach, it is taken into account that principle axes of orthotropy follow material's rigid rotation. Therefore, calculations are performed in the local material coordinate system. The rotation tensor $\mathbf{R}$ is determined experimentally on the basis of the displacement field using polar decomposition of the deformation gradient $\mathbf{F}$. On the basis of the coupled DIC and IRT analyses, the distributions of the energy dissipated as heat are determined using the newly developed method. Similarly as in [3,4], the method is based on the determination of heat sources from the transient heat conduction equation:

$$\varrho c\dot{T} = k\Delta T + \dot{q}_V, \tag{1}$$

where ϱ is the density, c is the specific heat and k is the heat conduction coefficient of the tested material and the $\dot{T} = \frac{\partial T}{\partial t} + \nabla T \cdot \mathbf{v}$ stands for the material derivative of the temperature. The term $\nabla T \cdot \mathbf{v}$ takes into account the change of the configuration of the material points during deformation process. The field analysis of the contributions of all the terms in the equation is performed with respect to the various process durations. The approach takes into account the thermoelastic effect and the heat exchange with the surroundings due to the heat convection and radiation. Therefore, the proposed method is universal and can be applied for various materials and wide range of deformation process conditions.

Experiment and results

The experiments were conducted on the 310S austenitic steel. The uniaxial tensile tests were performed using MTS 858 testing machine with the strain rates: $\dot{\varepsilon} = 10^{-2}s^{-1}$, $\dot{\varepsilon} = 10^{-1}s^{-1}$ and $\dot{\varepsilon} = 10^{0}s^{-1}$. During experiments the opposite surfaces of the sample were observed in the visible and infrared ranges, using pco.edge 5.5 and ThermaCam Phoenix IR cameras, respectively. On the basis of the obtained visible range image sequences, the displacement fields were determined using our own implementation of 2D digital image correlation algorithm [5]. Based on the determined evolutions of the displacement and temperature fields, the energy balance components were obtained using the proposed approach. In Fig. 1 the distributions of the displacement gradient component H_{yy} and the angle of material rotation R_z (with respect to z axis), which were used in the stress field calculation are presented. At the same figure, the distributions of the stress components σ_{yy} and σ_{xy}, obtained for various strain-rates are presented. As it is seen, in the considered strain rate range, the strain rate affects the onset of the localisation of plastic strain as well as the corresponding stress fields.

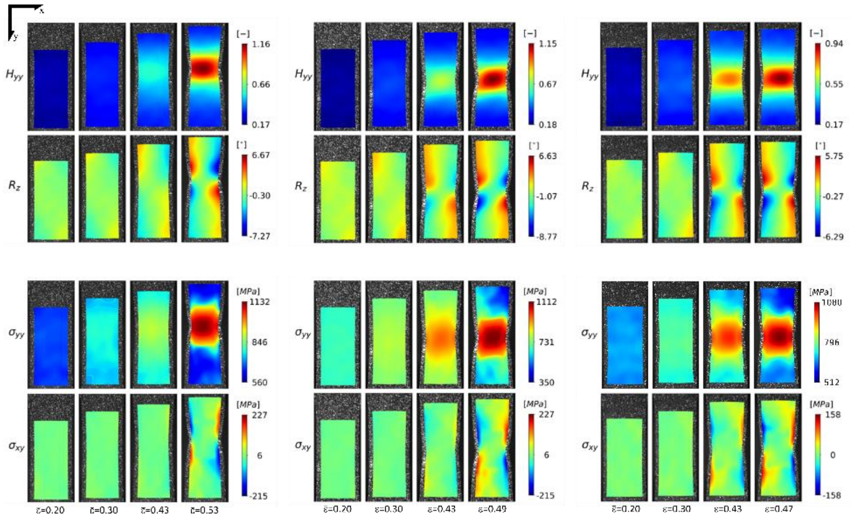

Fig. 1.

In Fig. 2 the distributions of the all terms of the heat diffusion equation (Eq. 1) are shown. The term $\varrho c\dot{T}$ is connected to the increase of the specimen's temperature, whereas the term $k\Delta T$ is connected to the heat conduction. As expected, the process duration significantly affects the obtained thermal fields. Depending on the strain rate, both the material derivative of the temperature $\dot{T}$ and the laplacian of the temperature ΔT differ from each other in terms of distribution and maximal values obtained. As a result, the proportions between the terms in the heat conduction equation, that is $\varrho c\dot{T}$ and $k\Delta T$ are significantly different for various process durations. Comparing the absolute values of these terms, it is seen that for the lowest strain rate process the heat conduction term $k\Delta T$ is dominant, whereas for the highest strain rate the situation is quite the opposite and the term $\varrho c\dot{T}$ is of major importance.

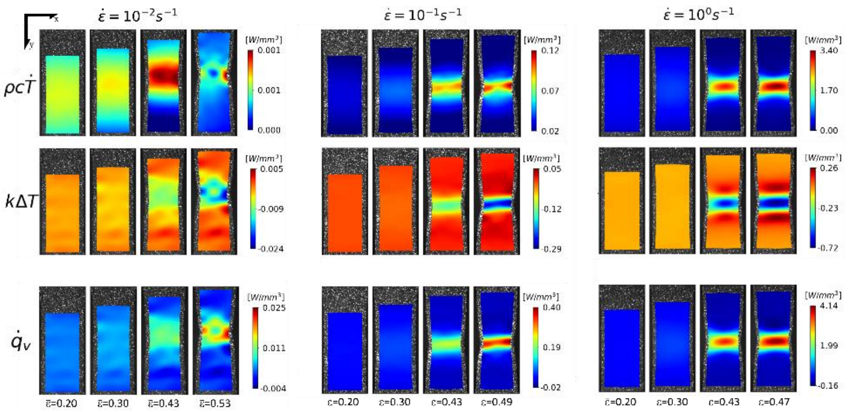

Fig. 2.

Presented approach allows for the determination of the evolution of plastic work and energy dissipated as heat in the area of plastic strain localisation. The proposed method is universal and can be applied for various materials and wide range of deformation process conditions.

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