DOI: 10.46793/41DAS2025.011L

IDENTIFICATION OF ENERGETIC AND DISSIPATIVE FLOW STRESS USING INFRARED THERMOGRAPHY

Nikola LALOVIĆ[1], Thomas BÖHLKE[2]

[1]0009-0002-6069-1088, Karlsruhe Institute of Technology (KIT) – Institute of Engineering Mechanics – Continuum Mechanics, Kaiserstr. 10, 76131 Karlsruhe, Germany, E-mail: nikola.lalovic@kit.edu;

[2]0000-0001-6884-0530, Karlsruhe Institute of Technology (KIT) – Institute of Engineering Mechanics – Continuum Mechanics, Kaiserstr. 10, 76131 Karlsruhe, Germany, E-mail: thomas.boehlke@kit.edu

1. Introduction

Based on own continuum-thermomechanical considerations extending [1], not only the energy stored and dissipated during plastic deformation of metals can be determined using infrared thermography (IRT), but also the flow stress can be additively separated into an energetic and dissipative component. An experimental-numerical methodology as well as some results for oxygen-free copper Cu-OF in pre-deformed and recrystallized condition are presented.

2. Materials and Methodology

To identify the energetic and dissipative components of flow stress, σ_{energ} and σ_{diss}, respectively, during plastic deformation, we combine quasi-static uniaxial tensile testing with in-situ infrared thermography (IRT). The experimental setup consists of a custom-built biaxial testing machine (based on the ZwickRoell Z150) and a high-resolution mid-wave infrared range (1.5–5.7 µm) camera (ImageIR 8340 S, InfraTec GmbH), offering high thermal sensitivity (<25 mK). Flat specimens of oxygen-free copper (Cu-OF, EN CW008A), prepared according to ISO 6892-1, were tested in both as-received (worked) and recrystallized conditions. Recrystallization was achieved by annealing at 400 °C for 30 minutes followed by water quenching.

To ensure accurate thermal measurements, the specimen surface facing the IR camera was coated black to achieve a high emissivity ($\varepsilon = 0.99$). Prior to testing, specimens were thermally equilibrated with the environment. Tests were conducted at a crosshead speed of 0.025 mm/s (initial strain rate ~9×10^{-4} s^{-1}), with mechanical and thermal data recorded at 10 Hz and 20 Hz, respectively.

Thermal data were processed using a digital image analysis routine based on the inverse solution of a simplified 2D heat conduction equation. Gaussian filtering and Laplacian-of-Gaussian smoothing were applied to mitigate noise amplification from derivative operations. A central region of interest (60×200 pixels) was extracted to avoid edge effects. The resulting pixel-wise field data enabled the quantification of internal heat sources, facilitating the separation of σ_{energ} and σ_{diss} contributions. The methodology closely follows and extends the framework proposed in [2], with recent adaptations for high-resolution IRT and advanced image processing. Key process parameters were identified through dedicated experiments and numerical optimization.

The characteristic time of heat transfer τ_{th}, which governs the rate of thermal exchange with the environment, was determined by heating a specimen uniformly and observing its cooling behavior via IRT. Assuming no internal heat generation, τ_{th} was optimized by minimizing the residual heat source field using a least-squares objective function.

The spatial smoothing parameter σ_{lap} for the Laplacian-of-Gaussian (LoG) filter was calibrated using synthetic temperature fields generated via finite element analysis (FEA) in Abaqus. These simulations modeled a constant internal heat source and fixed boundary temperatures. Gaussian white noise was added to match experimental conditions. The optimal σ_{lap} was found by minimizing the deviation between the reconstructed and simulated heat source fields. Both optimization problems were solved using the L-BFGS algorithm with multiple randomized initializations to ensure robustness. This methodology is similar to the one described in [3].

3. Results

Key parameters for thermal image analysis were identified through dedicated experiments and simulations. The characteristic time of heat transfer was determined from cooling tests on insulated specimens, yielding $\tau_{th} = 320$ s. Its sensitivity to temporal and spatial filtering parameters (σ_t, σ_{xy}) was found to be minimal. The optimal LoG filter parameter ($\sigma_{lap} = 22$ px) was identified using finite element simulations with added Gaussian noise averaging over multiple noise realizations.

Using these calibrated values, deformation-induced heat sources were reconstructed from infrared thermography data and used to decompose the flow stress into energetic and dissipative components. Mechanical testing showed minimal scatter. For worked Cu-OF, the dissipative stress component dominated the early plastic regime, while the energetic component exhibited a sharp initial drop followed by a gradual increase. This behavior might be attributed to microstructural reorientation due to the change in deformation path. In contrast, recrystallized Cu-OF showed a more balanced evolution, with the energetic stress steadily increasing and contributing up to one-third of the total flow stress at higher strains.

The Taylor-Quinney factor, defined as the ratio between dissipated heat power and mechanical work power supplied, stabilized around 0.7 for both conditions, with an initial overshoot observed in the recrystallized state. These findings can serve as a validation of the specific setup and the method's capability to resolve the thermomechanical response and provide a robust experimental basis for validating constitutive models that account for energy partitioning during plastic deformation.

4. Conclusions

A custom tensile setup, high-resolution thermal imaging, and a dedicated image processing routine enabled spatially and temporally resolved reconstruction of deformation-induced heat sources, accurate evaluation of the heat conduction equation and subsequent stress partitioning. The results show that both stress components evolve with plastic strain and are path-dependent, challenging the assumption of constant dissipative stress. The Taylor-Quinney factor derived directly from experimental data remained relatively stable during monotonic loading. Overall, the method provides a robust, non-invasive approach for quantifying internal energy storage and validating thermomechanically consistent constitutive models, offering new experimental insights into the coupling between mechanical work and thermal dissipation. The method's potential to infer microstructural evolution from macroscopic measurements represents a promising direction for future research.

References

[1] Rosakis, P., Rosakis, A.J., Ravichandran, G., Hodowany. J. A thermodynamic internal variable model for the partition of plastic work into heat and stored energy in metals. *J Mech Phys Solids*, 2000, 48(3), 581–607.

[2] Chrysochoos, A., Louche, H. An infrared image processing to analyse the calorific effects accompanying strain localisation. *Int J Eng Sci*, 2000, 38(16), 1759–88.

[3] Delpueyo D, Balandraud X, Grédiac M. Heat source reconstruction from noisy temperature fields using an optimised derivative Gaussian filter. *Infrared Phys Techn*, 2013, 60, 312–22.