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Analysis of the work-to-heat conversion beyond the necking onset in non isothermal tensile tests

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When metals undergo plastic deformation, some of the plastic work is stored in the material as defects, while the rest is dissipated as heat. In thermomechanics, the fraction of plastic work converted into heat is referred to as the Taylor-Quinney coefficient (TQC). At high strain rates, temperature increases in the material and can significantly influence its mechanical behavior. Therefore, accurately predicting temperature fields and the resulting mechanical response requires careful consideration of self-heating. Temperature increases are particularly critical during localized deformation, making tests that involve localization useful for understanding the dissipation of plastic work into heat up to large strains.
This study focuses on the post-necking phase of tensile tests conducted on cylindrical dog-bone samples. The aim is to present efficient methods for investigating the work-to-heat conversion using post-necking data, regardless of whether adiabatic conditions are verified. The methods involve recording tests with optical and infrared (IR) cameras with adequate temporal and spatial resolution, in order to fully exploit the heterogeneous fields and to improve the reliability of the results. A key difference from other studies is that the Digital Image Correlation (DIC) technique was not used to reduce experimental complexity and avoid issues related to speckle damage. Instead, backlight images were acquired and only the necking silhouette was considered for strain analysis thanks to a method previously developed by the authors. This is referred to as the "Database approach" since it consists of searching for the experimental specimen's shapes within a database built from finite element (FE) simulations. This method offers a way to determine the equivalent plastic strain on the specimen's surface with minimal experimental and computational effort, without assuming uniform strain across cross-sections. Additionally, it allows for estimating the equivalent stress experienced by material points on the sample's surface.
To investigate the TQC under adiabatic conditions, these strain and stress fields (available in an Eulerian perspective) must be converted into Lagrangian fields to compute the plastic work executed on various material points. Similarly, thermal fields recorded by the IR camera must be transformed into Lagrangian fields to compute the thermal history of material points. Such Eulerian-to-Lagrangian conversion is possible thanks to the same database used for strain and stress analysis, which allows for tracking material points even in case of backlighting. Finally, for each material point, the time evolution of both temperature and plastic work is known, allowing the estimation of the TQC. This approach, referred to as "Direct approach", gives reliable results provided that adiabatic conditions are verified.
For addressing non-adiabatic conditions another method is proposed. This is a preliminary approach which involves iteratively running thermal-structural FE simulations and adjusting the TQC based on comparisons between experimentally measured and numerically computed temperature distributions. Only conduction with constant thermal conductivity is considered as additional heat loss. From a mechanical perspective, the plastic flow curve used in the FE model must already be determined prior to iterations, without assuming specific TQC. This is achieved by combining Eulerian fields of strain, strain rate, and stress from the database approach with the Eulerian temperature field from the IR camera. The resulting point cloud, representing the material's response, is fitted to the desired model and used in FE simulations. Hence, the iterative approach can focus only on determining heat conversion.
Both the direct and iterative approaches were successfully tested against numerical benchmarks, encouraging their application in an experimental case study. The material tested was 17-4PH martensitic stainless steel, known for its moderate strain rate sensitivity and substantial self-heating due to low thermal conductivity. Tests were performed at room temperature and at nominal strain rates of 1, 10, and 1000 s^{-1}. Both proposed methods produced comparable results at higher strain rates where adiabatic conditions were met. At a nominal strain rate of 10 s^{-1}, conduction effects began to affect the results, causing limited discrepancies between

the two methods. For the 1 s^{-1} tests, conduction effects were more pronounced, and only the iterative approach accurately predicted the temperature distributions by identifying an appropriate TQC.
In conclusion, the results demonstrate the practical applicability of the proposed methods. The direct method is more computationally efficient, while the iterative approach is more general and shows promising results, despite being in its preliminary stage. Both methods do not require the use of DIC, which offers a significant reduction in experimental effort.

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