An Engineering Approximation On The Transformation Of Plastic Work Into Heat At Various Strain Rates And Stress States

Author(s):
Li, Xueyang; Roth, Christian; Grolleau, Vincent; Mohr, Dirk

Publication date:
2025

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000748033

Originally published in:
MATEC Web of Conferences 408, https://doi.org/10.1051/matecconf/202540802017

An Engineering Approximation On The Transformation Of Plastic Work Into Heat At Various Strain Rates And Stress States

Xueyang Li[1,2*], *Christian C.* Roth[1], *Vincent* Grolleau[1,3], and *Dirk* Mohr[1]

[1]Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
[2]inspire AG, Zurich, Switzerland
[3]Univ. Bretagne Sud, UMR CNRS 6027, IRDL, F-56100 Lorient, France

Abstract. Accurate estimation of plastic work conversion into heat is crucial for analyzing metals under dynamic deformation. This study investigates DP800 sheet metal specimens across nine strain rates (0.001/s to 150/s) using notched tension (NT) and shear (SH) specimens to explore stress-state effects. Surface strain fields are monitored via digital image correlation (DIC) using a high-speed optical camera, while temperature rise due to plastic dissipation is measured using a high-speed infrared camera. A temperature rise of 170K is observed at 150/s, with minimal rise at 0.001/s. A Hill'48 yield surface combined with a modified Johnson-Cook hardening law accurately predicts force-displacement and strain histories. We compare two methods of treating the conversion of the plastic work into heat: (1) coupled thermo-mechanical simulations, which are accurate but computationally expensive, and (2) treating temperature as an internal state variable, neglecting heat transfer. We then propose a transition function incorporating both strain rate and stress state dependencies, enabling the internal variable method to achieve comparable accuracy to coupled thermo-mechanical simulations with a marginal increase in computational cost over pure mechanical analysis.

Keywords: Thermo-mechanical analysis; Stress state dependency; Adiabatic heating; Dynamic behavior of materials

1 Introduction

Metallic materials subjected to large deformations at high strain rates often experience significant temperature rises due to the conversion of plastic work into heat. The Taylor-Quinney coefficient, often assumed as 0.9, represents this fraction in engineering. At ultra-fast strain rates, assuming adiabatic conditions gives accurate results. However, for intermediate strain rates (0.01/s–10/s), coupled thermo-mechanical analysis is necessary to capture transient heat conduction under complex boundary conditions. While effective, these coupled analyses are computationally expensive. Transition functions [1-5] have been introduced to estimate temperature evolution in pure mechanical analyses by incorporating strain rate-dependent weighting for the shift from isothermal to adiabatic conditions. These transition functions treat temperature as an internal variable of the material, allowing signification acceleration of numerical simulations through mass-scaling methods.

In this study, we observe that the fraction of plastic work converted to heat varies between shear and tensile stress states, indicating that transition functions should account for both strain rate and stress state dependencies.

2 Results

2.1 Material and Specimen

In this study we investigate a DP800 steel sheet of 1.6mm thickness. Fig. 1 shows the geometries of shear (SH) and notched tension sample with 20mm radius cutout (NT20).

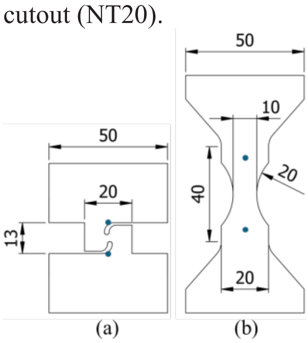

Fig. 1. Sample geometries for material characterization (a) shear and (b) notched tension sample with R=20mm cutout (NT20). The blue dots represent the positions of virtual extensometers.

* Corresponding author: xueyang.li@inspire.ch

2.2 Experimental Setup and Results

The shear and notched tension experiments are performed with displacement control on a hydraulic testing machine. A speckle pattern is painted on one side of the specimen for digital image correlation (DIC), and monitored using a high-speed camera (Photro SA-Z). A graphite-based paint is applied to the other side for temperature measurement using an infrared camera (FLIR X6801SC). Both cameras are triggered by the rise in force signal and operate at 1000 Hz.

Fig. 2 presents the force and temperature histories from NT20 experiments conducted at 500 mm/min (solid dots). The test duration is approximately 0.3 seconds, with a final surface temperature of 153°C recorded on the sample. A notable temperature increase occurs after necking begins. In contrast, shear experiments at 500 mm/min (Fig. 3) exhibit a lower final temperature of 97°C.

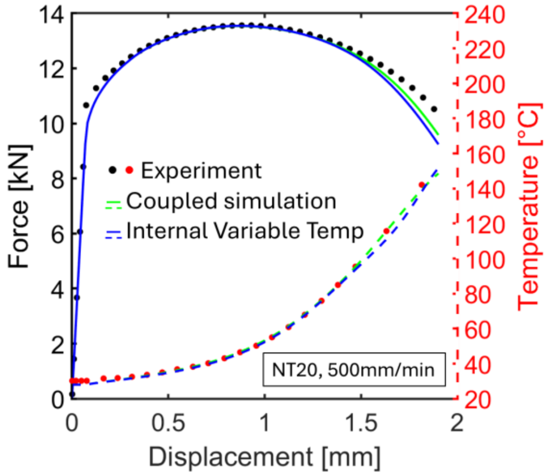

Fig. 2. Force-displacement and temperature history of NT20 experiment at 500mm/min.

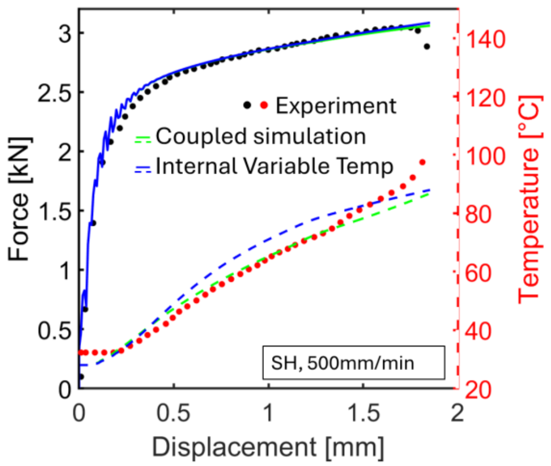

Fig. 3. Force-displacement and temperature history of shear (SH) experiment at 500mm/min.

2.3 Numerical modelling

The DP800 steel is modeled using Hill'48 yield surface with non-associated flow rule [1], incorporating Johnson-Cook terms [6] to capture strain rate and temperature effects. As an engineering practice, the Taylor-Quinney coefficient is set to be 0.9. We perform finite element simulations using Abaqus/Explicit, with three dimensional hexahedral (brick) elements C3D8RT for coupled thermo-mechanical simulation, and C3D8R when treating temperature as an internal variable. Fig. 4 provides a schematic drawing for the transition function.

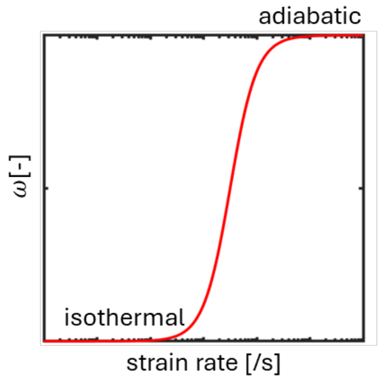

Fig. 4. Schematic drawing for the transition from isothermal to adiabatic conditions as a function of strain rate.

Fig. 2 and 3 show that both the internal variable method (blue) and the coupled simulation (green) accurately predict force-displacement and temperature evolution, aligning well with experimental data. Both methods estimate the terminal temperature within a few degrees for tension and shear tests. On a 12-core CPU, the coupled FEA of the NT20 geometry takes 187 minutes, while the internal variable method completes in just 12 minutes, achieving a 15-fold improvement in computational efficiency.

3 Conclusions

We propose a transition function that incorporates dependencies on both strain rate and stress state when treating temperature as an internal variable. This approach enables the internal variable method to match the accuracy of coupled thermo-mechanical analysis while maintaining the computational efficiency of pure mechanical analysis.

References

1. C. C. Roth, D. Mohr, Int. J. Plast., **56**, 19 (2014)
2. S. Klitschke, A. Trondl, F. Huberth, and M. Liewald., IOP Conf. Ser. Mater. Sci. Eng., **418**, (2018)
3. D. Rittel, L. H. Zhang, S. Osovski, J. Mech. Phys. Solids, **107**, 96 (2017)
4. X. Li, C. C. Roth, D. Mohr, EPJ Web of Conferences, **250**, (2021)
5. V. Langi, G. C. Soares, S. Ahmed, P. Peura, M. Hokka, Mater. Sci. Eng. A, **865**, 144659 (2023)
6. G. R. Johnson, W. H. Cook, Eng. Fract. Mech., **21**, 31 (1985)