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Determination of the fraction of plastic work converted into heat in metals

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ABSTRACT

A new approach for measuring the fraction of plastic work that is converted into heat (also known as the Inelastic Heat Fraction, IHF or the Taylor–Quinney coefficient) during the plastic deformation of metals is proposed in this paper. The method is based on the uniaxial tension of a slender metal rod, with the lateral surface of the rod being under well-defined thermal boundary conditions. The corresponding one-dimensional model of heat transfer during the process is considered in the form that accounts for all major effects. The current approach is based on the fact that the unknown IHF enters this heat equation linearly and therefore can be found explicitly if all the other terms are accounted for experimentally. The experimental procedure developed is based on local measurements of temperature and its gradients and of strain and velocity with the aid of an infrared (IR) camera and a Digital Image Correlation (DIC) system, respectively. A vacuum tube that encloses the specimen was designed to provide control over the heat losses due to convection during the test. A fitting method based on Hermite splines allows us to deal with smooth functions instead of noisy data sets, improving the overall accuracy of the procedure. The IHF is obtained as a function of plastic strain for a set of strain rates for four materials: 303 and 316 stainless steels, commercially-pure titanium (CP Ti) and the alloy Ti–6Al–4V. The findings indicate that the IHF is not constant with the plastic strain and furthermore, it is also sensitive to the strain-rate. Our measurements revealed that depending on the material the IHF was generally between 0.55 and 0.8, but it could also be as low as 0.3.

1. Introduction

During plastic deformation of metals only a relatively small amount of the expended plastic work is spent on actual deformation – change in shape, texture, etc. This part is usually called the stored or latent energy. In contrast, the majority of the applied work is dissipated into the surroundings of the deforming material as heat. One of the fundamental questions is the proportion between the stored and dissipated parts of the total plastic work.

The dissipation of a fraction of the plastic work as heat is in essence perceived macroscopically as deformation-induced heating. This continuous change in the temperature during deformation affects the recorded mechanical response. For example, in the case of a tension test, heating can reduce the flow curve and furthermore act as an imperfection that will precipitate the localization of deformation and limit the apparent ductility of the material. There are multiple investigations of this problem, e.g., Chrysochoos et al. (1989), Cullen and Korkolis (2013), Kamlah and Haupt (1997), Mareau et al. (2013), Rusinek and Klepaczko (2009), Zhang and Shim (2010), Dumoulin et al. (2010), Kim and Wagoner (1987), Lin and Wagoner

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(1987), Gao and Wagoner (1987), Subhash et al. (1997) among others. In a recent investigation on 304 stainless steel (Cullen and Korkolis, 2013), it was determined that the material heated up significantly and non-uniformly, even under quasistatic conditions. Furthermore, with the aid of full-field measurements of strain and temperature, it was determined that the non-uniform heating preceded strain localization and led to an early failure, in comparison to isothermal testing.

The first attempts to determine the IHF were by Farren and Taylor (1925) and Taylor and Quinney (1934). In these works, the concepts of stored and dissipated energy fractions were introduced and estimated experimentally. The fraction of dissipated energy (also called Taylor–Quinney coefficient, Inelastic Heat Fraction or IHF) was measured to be around 90% for a variety of metals. A theoretical study on stored energy was performed in Stroh (1953). A comprehensive overview of works published in the first half of the XX century and dedicated to IHF measurements is included in Titchener and Bever (1958) and Bever et al. (1973).

Numerous new approaches to the problem were developed during the past 20–30 years. First of all there are high strain-rate techniques, which use Kolsky or Hopkinson bars and an infrared (IR) camera (Mason et al., 1994; Kapoor and Nemat-Nasser, 1998; Rittel, 1999; Hodowany et al., 2000) or radiometry (Macdougall, 2000). The idea is to perform the test as fast as possible to make it almost adiabatic (i.e., to reduce the heat losses) and capture the amount of heat generated using an IR detector. Such experiments are particularly suitable for the IHF measurements under dynamic loading conditions, provided that accurate measurements can be made throughout the very short duration of the test.

Alternatively, hybrid approaches were proposed. The idea here is to couple a heat transfer analysis, which includes the unknown IHF, with experimental measurements. A hybrid method based on fatigue experiments was proposed in Wong and Kirby (1990). Another hybrid iterative scheme based on the quasistatic uniaxial tension test and the solution of an initial-boundary value problem was developed in Zehnder et al. (1998). A finite element updating inverse method, coupled with strain and temperature data was described in Pottier et al. (2013). By using hybrid methods, IHF can be determined for low and intermediate strain-rates. Unlike methods based on high strain-rate tests, the hybrid methods allow the use of simpler equipment. On the other hand, precise modeling of the heat losses is required as well.

Another set of methods is using different thermodynamic frameworks to estimate IHF theoretically. The corresponding analyses were performed in Rosakis et al. (2000), Longère and Dragon (2008a,b), Vivier et al. (2009) and Zaera et al. (2013). A variational formulation was considered in Stainier and Ortiz (2010). An analysis based on a dislocation plasticity model was presented in Benzerga et al. (2005).

In this paper, we propose a method of measuring the IHF as a function of the plastic strain for various strain-rates using a combination of experiments and analysis. We consider the uniaxial tension of a slender metal rod which resembles a one-dimensional body, simplifying the modeling significantly. Instead of solving the governing partial differential equation (PDE) as in Zehnder et al. (1998), which requires precise knowledge of the thermal boundary conditions, we propose a different approach. Since IHF comes into the PDE linearly, we determine experimentally all other terms in the PDE and then solve it algebraically for the IHF. To eliminate the effect of parameters that cannot be easily measured with precision, such as the film coefficient along the deforming rod, the specimen is surrounded by vacuum, eliminating convective heat losses. Local temperature and temperature gradients are measured with an IR camera. At the same time, local kinematics measurements are performed using the non-contact, full-field Digital Image Correlation (DIC) system. An Eulerian description of heat transfer is adopted, to aid with the experimental measurements.

An advantage of the proposed method is that it involves only the local heat balance at a fixed point in space. Therefore, there is no effect of unknown boundary conditions at the ends, nonuniform heat transfer conditions along the specimen, etc., and only accurate local measurements are needed. This minimizes the number of assumptions needed and increases the robustness and accuracy of the method. Another advantage is that there is no need to solve the nonlinear PDE.

We begin by describing the theoretical framework, which involves an Eulerian description of heat conduction. We proceed to outline the experimental set-up that we used. We then describe the experiments that we performed on four metals and alloys (303 and 316 stainless steel, commercially-pure Titanium and Ti–6Al–4V) and the corresponding IHF that we determined for each of them over a range of strain-rates.

2. Description of the proposed method

2.1. Integral and differential Inelastic Heat Fraction (IHF)

The process we are considering is the plastic deformation of a homogeneous solid body and its resulting, deformation-induced, heating. The differential (or instantaneous) IHF β (also noted as β_{diff} in literature; here the symbol β is adopted for simplicity) is defined as the ratio of infinitesimal change in the heat generated to the corresponding infinitesimal change in the plastic work done. Also, the integral (or total) IHF β_{int} is defined as the ratio of finite change in heat generated to the finite change in plastic work done during a given finite deformation. If the heat and plastic work are denoted as Q and W^p, then both definitions of the IHF can be written in the following way:

$$\beta = \frac{\dot{Q}}{\dot{W}^p}, \tag{1}$$

$$\beta_{\text{int}} = \frac{Q}{W^p}, \tag{2}$$

where upper dot means time derivative or rate.