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On the relation between shape imperfections of a specimen and necking growth rate under dynamic conditions

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ABSTRACT

In this work, the growth rate of necks formed in dynamically loaded tensile steel samples is investigated. For that purpose, a combined experimental-numerical approach, in which the experimental results are systematically compared with finite element calculations, has been developed. The specimens have a machined sinusoidal geometrical imperfection that covers the whole gauge, introducing a characteristic wavelength in the samples. For a given cross-section diameter, specimens with 6 different gauge lengths (i.e. 6 different specimen wavelengths) were tested. Using a high-speed camera, we measured the time evolution of the radial contraction of the central section of the samples (central section of the neck), thus obtaining the growth rate of the necks. The experiments show that the speed of growth of the necks increases non-linearly with the specimen wavelength (concave-downward shape) until saturation is reached for the longest tested specimens. Numerical simulations performed for the strain rates attained in the experiments (from 900 s^{-1} to 2100 s^{-1}) confirm this trend and demonstrate that the damping of short specimen wavelengths is caused by stress multiaxiality effects. Numerical simulations performed for strain rates greater than those attained in the experiments (above 7500 s^{-1}) show that long specimen wavelengths become damped by inertia effects at sufficiently high strain rates. For strain rates greater than 7500 s^{-1}, the maximum growth rate of the neck corresponds to an intermediate specimen wavelength defined by the joint action of stress multiaxiality and inertia on damping short and long wavelengths, respectively. Altogether, our experimental and numerical results suggest the existence of a specimen wavelength that, when inertia effects become important, determines the maximum growth rate of dynamic necks, in agreement with the predictions of the dynamic stability analyses developed by Molinari and co-workers (Fressengeas and Molinari, 1985, 1994; Mercier and Molinari, 2003, 2004).

1. Introduction

The rapid radial expansion of radially symmetric structures like rings (Gourdin, 1989; Grady & Benson, 1983; Janiszewski, 2012; Zhang & Ravi-Chandar, 2006), tubes (Goto et al., 2008; Hiroe, Fujiwara, Hata, & Takahashi, 2008; Zhang &

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Ravi-Chandar, 2008, 2010) or hemispheres (Mercier, Granier, Molinari, Llorca, & Buy, 2010) is the most common experimental configuration used to investigate the processes of multiple necking and fragmentation of metallic materials at high strain rates. The radial symmetry of these problems minimizes the propagation of stress waves within the circumferential direction of the specimens (before the onset of necking), which allows for the inception and development of multiple localization patterns. These experimental works (e.g. Fig. 8 in Zhang & Ravi-Chandar, 2008) have shown that: (1) the number of necks incepted in the samples increases and (2) the variability in the (absolute) distance between necks decreases as the specimen expansion rate increases.

The theoretical framework originally developed by Mott (1947), which postulates that the distribution of necks is directly connected to the statistical material property and microstructure variations, has been traditionally used to rationalize previous experimental observations, see for instance (Zhang & Ravi-Chandar, 2008). It was explained that the number of necks increases and the distance between necks decreases with the loading rate because the unloading waves that emanate from the localization points propagate a shorter distance as the expansion rate increases. This allows for the activation of a larger number of material defects, which lead to a larger number of necks, as the loading rate increases.

An alternative theoretical framework was developed by Molinari and co-workers (Fressengeas & Molinari, 1985, 1994; Mercier et al., 2010; Mercier & Molinari, 2003, 2004) who approached the multiple necking problem using dynamic stability analyses. The technique consists of adding a small perturbation to the fundamental solution of the problem to determine whether a neck-like deformation field can exist (Guduru & Freund, 2002). This method predicts that the perturbation only grows for a finite number of wavelengths: short wavelengths (short necks) are damped by stress multiaxiality effects and long wavelengths (long necks) by inertia. It was concluded that the growing wavelength modes define the range of neck sizes (i.e. neck spacings) that can be found in the localization pattern. The specific wavelength mode that grows the fastest, referred to as the critical wavelength, is assumed to determine the average neck spacing in the localization pattern. The dynamic stability analyses complement the classical statistical theory of Mott (1947) and identify a deterministic component within the mechanisms which control the inception and development of the multiple necking pattern.

The predictions of the dynamic stability analyses have been confirmed, using finite element calculations, in various recent works. Rodríguez-Martínez, Vadillo, Zaera, and Fernández-Sáez (2013) simulated the ring expansion problem including in the outer perimeter of the samples an array of periodic (neck-like) geometric imperfections of predefined amplitude and wavelength. In agreement with the stability analyses, the numerical computations showed that sufficiently long wavelength imperfections are completely suppressed by inertia and sufficiently short wavelength imperfections are completely suppressed by stress multiaxiality effects. Furthermore, using a unitary axisymmetric cell model which included a sinusoidal spatial imperfection, Rodríguez-Martínez, Vadillo, Fernández-Sáez, and Molinari (2013) also demonstrated the existence of a wavelength mode that, at high strain rates, determines the minimum investment of energy to trigger a neck. It was suggested that this specific wavelength mode possesses definite resemblance with the so-called critical wavelength obtained in the linear stability analyses. Nevertheless, the numerical results obtained from the unitary cell calculations have never been compared with experiments of the same kind, and this is the scientific gap that we aim to cover with our research.

In this paper we present the first unitary cell experiments ever performed to assess whether, in agreement with the unitary cell calculations and the linear stability analysis, there are specific wavelength modes that grow faster than others (i.e. require less energy to develop). For that purpose, we have tested using a Kolsky tensile apparatus steel cylindrical specimens which include a sinusoidal imperfection that mimics the geometrical wavelength included in the unitary cell calculations (Rodríguez-Martínez, Vadillo, Fernández-Sáez, et al., 2013). Various specimen sizes, i.e. various specimen wavelengths, have been tested. In all the tests performed the neck is incepted in the central section of the sample, where the amplitude of the imperfection is maximum. The experiments have been recorded using a high-speed camera which enabled to measure the time evolution of the radial contraction of the neck. The key result of this paper is to show experimentally that the rate of growth of the necks depends on the specimen wavelength. Moreover, we have compared our experimental results with unitary cell calculations for different strain rates that we have specifically developed for this purpose. The comparison shows, in agreement with earlier theoretical and numerical works (Rodríguez-Martínez, Molinari, Zaera, Vadillo, & Fernández-Sáez, 2017; Xue, Vaziri, & Hutchinson, 2008) that, when inertia effects become important, there are specific wavelengths which require less investment of energy to develop a neck.

2. Experimental setup

The dynamic tensile experiments were performed using a standard 12.7 mm diameter Kolsky tensile apparatus (Harding, Wood, & Campbell, 1960; Kolsky, 1949) made of hardened C300 Maraging steel bars. The apparatus was loaded using a 400 mm long tubular projectile, launched toward a flange located at the end of the incident bar. In order to prevent specimen reloading, a momentum trap was brought initially in contact with the loaded flange of the incident bar, whose length was identical to that of the projectile bar. Additional details of the experimental arrangement can be found in Rittel, Rotbaum, Rodríguez-Martínez, Sory, and Zaera (2014) and Rotbaum and Rittel (2014).

The experimental specimens were machined from SAE 12L13 free cutting steel bars in as-received condition. As illustrated in Fig. 1, the cylindrical samples (round cross-section) used in the experiments have a sinusoidal geometrical imperfection generated during the machining process. As mentioned in the introduction, we aim to reproduce experimentally the numerical model used in Rodríguez-Martínez, Vadillo, Fernández-Sáez, et al. (2013) to identify the existence of a neck size that minimized the energy required to trigger material failure under dynamic tension. The geometrical imperfection is described