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Characterisation of high rate plasticity in the uniaxial deformation of high purity copper at elevated temperatures

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ABSTRACT

In uni-axial compression at strain rates above $10^4\ \mathrm{s}^{-1}$, FCC metals exhibit a rapid increase in strength. Mechanisms proposed to be responsible for this transition can be broadly split into two categories; that mobile dislocation velocities become limited by quasi-viscous scattering from phonons, or that some change occurs in the evolution of the materials dislocation structure. The relative contribution of each mechanism is difficult to identify, in part due to a scarcity of experimental measurements in varying deformation conditions. In this paper, we perform uni-axial compression experiments that reach rates between 10^4 and $10^5\ \mathrm{s}^{-1}$, at temperatures between 300 and 600 K. Analysis of the data at 0.1 strain shows both the absolute and relative levels of thermal softening increase with strain rate, an anomalous result in comparison to both existing models and measurements below the transition.

1. Introduction

Above uni-axial true strain rates, $\dot{\varepsilon}$, of $10^4\ \mathrm{s}^{-1}$, FCC metals exhibit a rapid rise in strength; a phenomenon initially observed by Follansbee, Regazzoni and Kocks (Follansbee et al., 1984). The original measurements from their study are depicted in Fig. 1, which shows how the stress required to continue deforming an oxygen free high conductivity (OFHC) copper varies at a fixed uni-axial strain, ε, as a function of strain rate. Importantly, in these measurements the strain rate remains approximately constant throughout deformation. The measurements have since been reproduced by numerous authors, and collated by Jordan et al. (2013).

The physical phenomena that have been proposed to explain the transition in behaviour can be broadly split into two categories. Firstly the speed of dislocations propagating strain is proposed to become limited by a quasi-viscous scattering from phonons in the lattice (Anderson et al., 2017; Rusinek et al., 2010; Nemat-Nasser and Li, 1998). The second is that a change occurs in the evolution of the internal dislocation structure (Armstrong and Walley, 2008; Armstrong and Li, 2015). Typically the change in dislocation evolution is predicted to result in an increase of the mechanical threshold (Gao and Zhang, 2012; Follansbee and Kocks, 1988), a state variable like parameter describing the stress required to initiate deformation in the absence of thermal effects (Follansbee, 2014).

A large number of both physical (Hunter and Preston, 2015; Goto et al., 2000; Hosseini and Kazeminezhad, 2009; Preston et al., 2003; Hansen et al., 2013; Langer et al., 2010; Huang et al., 2009) and phenomenological (Gao and Zhang, 2012; Gould and Goldthorpe, 2000; Sung et al., 2010; Baig et al., 2013; Khan and Liu, 2012; Molinari and Ravichandran, 2005; Zerilli and Armstrong, 1987; Regazzoni et al., 1987) models now exist, many more are collated by Salvado et al. (2017). In order to discern between the plethora of available models, with varying emphasis on the two competing mechanisms, experimental measurements under many different conditions are required.

One approach for comparing models is through their predictions of material behaviour at varying temperatures and strain rates.

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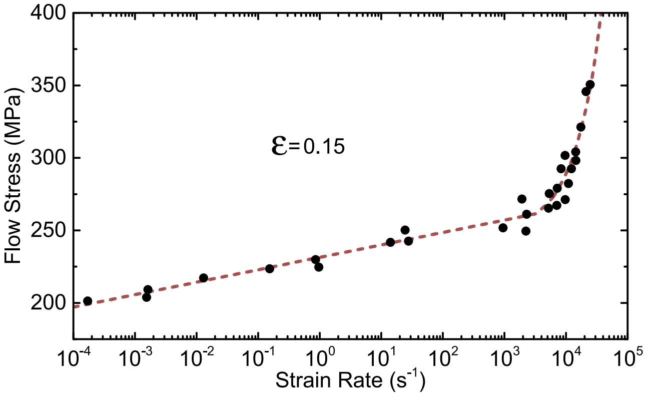

Fig. 1. The flow strength of an OFHC Cu at true 0.15 strain measured as a function of uniaxial strain rate, $\dot{\varepsilon}$. The dashed line is to guide the eye. Data taken from Follansbee et al. (Follansbee et al., 1984).

These are useful as drag mechanisms have different temperature dependencies to structural ones. Despite the widespread use of the uniaxial stress geometry for model parametrisation, exemplified in data collation by Liang and Khan (1999), Jordan et al. (2013) and Hansen et al. (2013) measurements at elevated temperatures and rates above $10^4\ \mathrm{s}^{-1}$ are sparse. The majority of measurements in that temperature and rate regime exist under conditions of shear strain (Frutschy and Clifton, 1998; Grunschel and Clifton, 2007) or the uni-axial strain conditions present in shock wave propagation (Kanel, 2014; Gurrutxaga-Lerma et al., 2017; Chen et al., 2017). Furthermore, in both cases measurements typically begin an order of magnitude above the transition rate. The aim of the current work is to extend miniaturised Hopkinson pressure bar experiments, used at very high rates, to elevated temperatures, allowing measurement of the response of metals in uni-axial stress conditions above $10^4\ \mathrm{s}^{-1}$. Such measurements should act to connect thermal behaviour both below and well above the transition, and will provide better tests of how models address the transition in a uniaxial loading geometry.

In section 2 we will first outline the most basic picture describing the combination of the two mechanisms, before progressing on to a brief discussion of more sophisticated models, at each point discussing relevant experimental studies. Section 3 outlines the experimental arrangement, with emphasis on reducing errors at increased temperatures and on the limitations of the resulting measurements. Finally, in section 4 we will discuss the results obtained in terms of both viscous and thermal activation mechanisms, using rudimentary manipulations to avoid restricting observations to the framework of any one particular plasticity model.

2. Background

The general motion of a dislocation is typically modelled as being either stationary (pinned) or in transit. Acceleration time-scales are considered negligible, being of the order of 10 ps (Gorman et al., 1969). The drift velocity of a single dislocation is therefore described as

$$\bar{v} = \frac{\lambda}{t_{pin} + t_{tra}}, \tag{1}$$

where λ is the “mean free path” between any two points at which a dislocation is pinned (Brown, 2012; Devincre et al., 2008), and varies with dislocation structure. The t terms are the time-scales of pinning and transit respectively.

Pinning, in its most simple form, is considered as when the strain fields of dislocations interact with those of immobile “forest” dislocations, typically by annihilating at a point and preventing motion until the lost dislocation segment can be regenerated (Hunter and Preston, 2015). Regeneration of the dislocation segment is typically modelled using transition state theory, commonly in an Arrhenius (1889) form,

$$t_{pin} \approx \frac{1}{f_D} exp\left[\frac{U(\hat{\sigma}, \sigma_p)}{k_B T}\right], \tag{2}$$

where f_D is the vibrational frequency of the dislocation. U is the remaining potential barrier given a structural “plastic” (Gould and Goldthorpe, 2000) or “threshold” (Regazzoni et al., 1987; Gao and Zhang, 2012) strength, σ_p, that would be required to deform the metal at 0 K and the applied stress $\hat{\sigma}$, typically after the subtraction of a small constant known as the “athermal” stress, σ_0, arising from “long range barriers” such as impurities and grain boundaries (Gao and Zhang, 2012). T is the absolute temperature and k_B is Boltzmann's constant. Due to false perturbation (Hunter and Preston, 2015) and relaxation (Hunter and Preston, 2015; Selyutina et al., 2016) considerations involved in this formulation, the model is incomplete. However it remains qualitatively similar enough to more rigorous approaches to allow use in the current discussion.

The true nature of pinning, especially in FCC metals, is much more complex. Different slip systems (Dequiedt et al., 2015) and dislocation reaction mechanisms (Kubin et al., 2003), such as locks (Hansen et al., 2013), pile-ups (Armstrong and Walley, 2008; Brown, 2012) and recovery Madec and Kubin (2017), must be accounted for. Whilst the mechanical threshold was originally posed as