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Strain rate influence on fracture development in experimental ductile multilayers

Enrique Gomez-Rivas *, Albert Griera

Departament de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain

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ABSTRACT

The far-field strain rate is a crucial parameter that controls the transition between brittle and ductile deformation. We have used analogue experiments to study the strain rate influence on the development of brittle fractures in a ductile composite material. Plasticine multilayer models were deformed under coaxial boundary conditions at three different strain rates to analyse the transition from non-localised deformation to the development of a brittle fracture network that accommodates part of the deformation. The results show that tension cracks and voids are the first macroscopic structures that nucleate after an early stage of ductile deformation. Coalescence and collapse of these structures lead to the development of brittle shear fractures. The evolution of fracture orientations, lengths and displacements was systematically analysed. The ratio of the accumulated fracture displacement *vs.* fracture length (d_{max}/L) depends not only on the total deformation, but also on the strain rate at which the system is deformed. The accumulated displacement with respect to fracture length increases with strain rate.

1. Introduction

In the brittle-to-ductile transition of continental crust displacement can be accommodated by networks of shear zones in which ductile and brittle deformation coexist (e.g. Passchier, 1984; Hobbs et al., 1986; Mancktelow and Pennacchioni, 2005; Fusseis et al., 2006; Mancktelow, 2006, 2008a; Pennacchioni and Mancktelow, 2007; Schrank et al., 2008). The localisation of brittle and ductile deformation is a multiscale phenomenon that has been extensively investigated from micro to large scale and by means of field, experimental and numerical studies (e.g. White et al., 1980; Bons and Jessell, 1999; Carreras, 2001; Marques, 2001; Schueller et al., 2005; Schöpfer et al., 2006; Liu and McVeigh, 2008). Several reasons have been proposed to explain the heterogeneous pattern of brittle and ductile strain localisation. They are mainly based on potential factors that control the intensity of deformation (e.g. confining and fluid pressures, temperature, etc.), the local deformation geometry or the evolution of mechanical properties during deformation (Sibson, 1980; Hobbs et al., 1986, 1990; Handy et al., 1999; Montesi and Zuber, 2002; Regenauer-Lieb and Yuen, 2003 and references therein; Jessell et al., 2005). Here, brittle behaviour is understood as deformation showing loss of cohesion along discrete surfaces, while ductile strain localisation is defined by zones of localised deformation with continuous variations of strain across their width and without loss of cohesion (e.g. Twiss and Moores, 1992; Fusseis et al., 2006). Therefore, ductile deformation can be distributed (i.e. non-localised) or localised (i.e. in shear zones).

Whereas the physics of fracture development processes in a brittle medium are relatively well-known (e.g. Mandl, 2000), the processes controlling the onset and network development of brittle fractures and ductile shear bands in a ductile medium (e.g. Barr and Houseman, 1992, 1996; Fusseis et al., 2006) is still a challenging topic. The influence of time on localisation and fracture network development in systems dominated by ductile flow remains a crucial question.

As a first-order approach, the onset and propagation of a fracture (tensional or shear mode) can be regarded as a competition between an external loading rate and the rate of stress relaxation by viscous flow (i.e. strain-rate dependent deformation; e.g. Mandl, 2000; Hubert-Ferrari et al., 2003). If the viscous flow is able to relax the loading stress, fractures will not nucleate and deformation will be homogeneously distributed within the material. On the contrary, if the loading rate exceeds the ability to relax the stress by viscous flow, there will be an increase in stress until the strength limit of the material is reached. Then, a brittle fracture network can nucleate and propagate and part of the deformation will be accommodated by fractures. Several authors, mainly in the field of metallurgy (e.g. Thomason, 1989), but also recently in geosciences (e.g. Weinberg and Regenauer-Lieb, 2010), use the term ductile fractures to describe the onset of brittle fractures during creep deformation and microvoid coalescence.

One of the most important parameters controlling the relationship between brittle and ductile deformation is the far-field strain rate. Generally, an increase of strain rate enhances fault slip rates and produces a higher release of the stored elastic energy during fracture

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* Corresponding author at: Present address: Mineralogie und Geodynamik, Institut für Geowissenschaften, Eberhard Karls Universität Tübingen, Wilhelmstr. 56, 72074 Tübingen, Germany. Tel.: +49 7071 29 73147; fax: +49 7071 293060.
E-mail address: enrique.gomez-rivas@uni-tuebingen.de (E. Gomez-Rivas).

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propagation (e.g. Perez, 2004). While fracturing in a brittle material is associated with high velocity propagation and low energy dissipation by plastic work, the propagation of brittle fractures in a ductile medium is strongly reduced by the increase of plastic strain work (i.e. strain hardening) surrounding crack tips (e.g. Perez, 2004). Therefore, time independent approaches to interpret these fractures are not useful, and the influence of ductile deformation on the evolution of the fracture network (i.e. initiation, propagation, coalescence, rotation, etc.) needs to be addressed.

Fig. 1 shows an example of an array of small-scale sharp and discrete fractures developed within a ductile shear zone from Cap de Creus (E Pyrenees, Spain). Bedding and foliation planes can be used as reference markers to unravel the heterogeneous displacement and strain gradients across and along the fractures. Normal to reverse drag folds or flanking structures (Grasemann and Stüwe, 2001; Passchier, 2001; Grasemann et al., 2003, 2005; Kocher and Mancktelow, 2005; Kocher and Mancktelow, 2006) and smooth-to-sharp cut-offs are observed, while ductile bending of marker planes can be recognised at fracture tip zones. This structure corresponds to the s-type of Grasemann et al. (2003) classification of flanking structures. The ratio between the maximum displacement (d_{max}) and fracture length (L) measured from these fractures ranges between 0.15 and 0.20, with strong gradients from the centre to the tips. These observations are in agreement with that of Gomez-Rivas et al. (2007) from a larger dataset of small-scale fractures in a ductile sheared quartzite, and also with that of Fusseis et al. (2006) and Schrank et al. (2008) from km-scale shear zones. Similar ratios can be observed in most of flanking structures shown by Grasemann and Stüwe (2001), Grasemann et al. (2003) and Grasemann et al. (2005). However, these d_{max}/L values are very different from the ones inferred from field studies of fractures in brittle media for single slip events and mature faults with large accumulated displacements, which are of the order of 10^{-2}–10^{-4} (Walsh and Watterson, 1987; Cowie and Scholz, 1992; Kim and Sanderson, 2005). In these situations higher strain rates than that affecting ductile shear zones are expected.

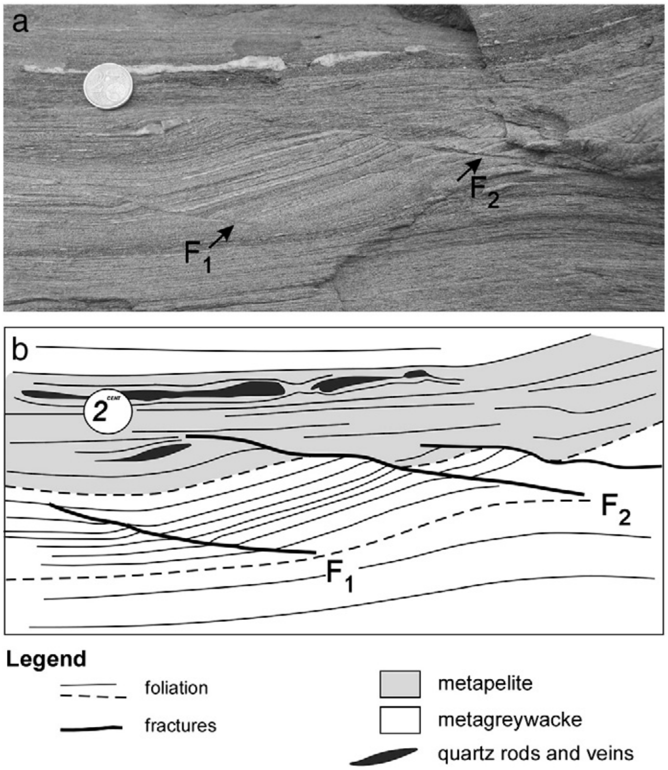

Fig. 1. Photograph showing an example of brittle deformation localisation in a ductile dominant system: (a) fractures oblique to anisotropy within a dextral-sense shear zone (greywacke) from Cap de Creus (E Pyrenees, Spain); (b) sketch showing the features observed in photo (a). Typical ratios between displacement and fracture length for these structures are in the range 0.1–0.3. The diameter of the 2-cent euro coin is 18.74 mm.

In this contribution we focus on the influence of strain rate on brittle localisation and fracture network development in ductile multilayers with low effective confinement. A series of plasticine multilayer models have been coaxially deformed at different strain rates in order to analyse the transition between models with non-localised deformation and systems in which deformation is partially localised in a fracture network. Layers were oriented parallel to the extension direction, trending to layer boudinage. The rheology of the analogue materials was first characterised with uniaxial compression and relaxation tests, in order to scale the models and to determine the mechanical reference framework. With this setup we aim to focus on situations of deformation at low effective confining pressure conditions, such as the case of ductile rocks at shallow conditions (e.g. salts, clays, etc.) and, especially, middle- to lower crust rocks with high fluid pressures or high tensional stress.

Our main objectives are: (a) to visualise and analyse the transition from non-localising to partially localised systems, (b) to analyse the occurrence and types of structures and fracture patterns within the models and their controls on the evolution of the deforming medium and, finally, (c) to explore the relationship between fracture propagation and displacement along them.

2. Materials and methods

Plasticine is a suitable material for modelling brittle and ductile deformation because it flows in a ductile manner but it can also be fractured depending on the imposed strain rate, temperature, effective confining pressure and boundary conditions. Our models were deformed using a strain rate and temperature controlled apparatus that can apply deformation from pure to simple shear ($0<Wk<1$).

Commercial plasticine, sold under the trademark Oclu-Plast (Barcelona, Spain), was used to build the models by stacking white and purple coloured layers (4 to 5 mm thick) oriented normal to the *Z*-direction (Fig. 2). Anisotropy is defined by small differences in the mechanical properties of layers of the two different colours and by the interfaces between them. In order to build the multilayer models the following procedure was used: (1) plasticine blocks were flattened using an industrial rolling pin inside a hard plastic frame, to create layers with the same thickness; (2) alternating layers of different colours were stacked; (3) the final block was slightly compressed perpendicularly to layering with small weights for approx. 24 h, and (4) the model was cut with a power saw to the final dimensions of

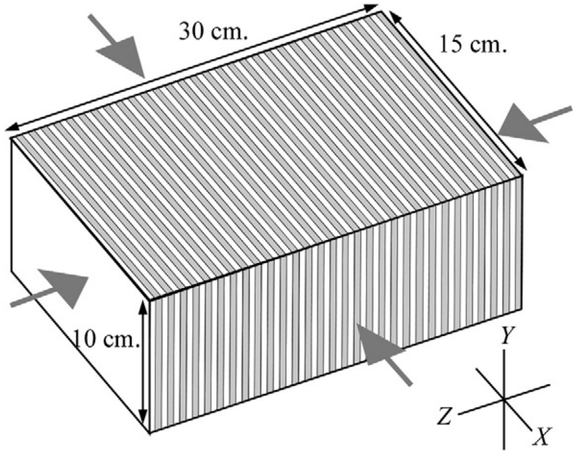

Fig. 2. Sketch of a multilayer model. Arrows show the direction of the principal stresses applied by the deformation apparatus. Initial layer thickness is ~4 mm.