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Influence of a low-viscosity layer between rigid inclusion and viscous matrix on inclusion rotation and matrix flow: A numerical study

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Abstract

We have used 2-D finite element modelling to investigate the influence of a permanent low-viscosity layer between matrix and inclusion on matrix flow and inclusion rotation under viscous simple shear flow. Rigid inclusions of different shape (circle, square, ellipse, lozenge, rectangle and skewed rectangles) and aspect ratio (R) were used. The calculated matrix flow pattern is neither bow tie nor eye-shaped. It is a new flow pattern that we call cat eyes-shaped, which is characterized by: (i) straight streamlines that slightly bend inwards at the inclusion's crests; (ii) elongate eye-shaped streamlines on each side of the inclusion; (iii) stagnation points in the centre of the eyes; (iv) absence of closed streamlines surrounding the inclusion; (v) changes in flow configuration with inclusion orientation; the lines of flow reversal bend and tilt, closed streamline circuits may disappear, and streamlines may bend outwards at the inclusion's crests.

Concerning inclusion rotation, the numerical results show that: (i) a low-viscosity layer (LVL) makes inclusions with $R=1$ rotate synthetically, but the rotation rate depends upon shape (circle or square) and orientation. Therefore, shape matters in the slipping mode. (ii) All studied shapes with $R>1$ rotate antithetically when starting with the greatest principal axis (e_1) parallel to the shear direction ($\phi=0°$); (iii) rotation is limited because there is a stable equilibrium orientation (ϕ_{se}) for all studied shapes with $R>1$. (iii) There is also an unstable equilibrium orientation (ϕ_{ue}), and both ϕ_{se} and ϕ_{ue} depend upon inclusion's R and shape.

The present numerical results closely agree with previous results of analogue experiments with a permanent low viscosity interface. Only minor deviations related with small shape differences were detected.

Keywords: Numerical modelling; Simple shear; Low-viscosity layer; Inclusion rotation; Cat eyes flow pattern; Stable equilibrium orientation

1. Introduction

Natural occurrences and recent analogue experiments show that a slipping inclusion/matrix bound-

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ary can be responsible for antithetic rotation and development of stable shape preferred orientations (SPO) in simple shear (e.g. Mancktelow et al., 2002; Ceriani et al., 2003; Marques and Bose, 2004; Schmid and Podladchikov, 2004). The flow of a viscous matrix in slipping or non-slipping contact with a rigid inclusion (slipping and non-slipping modes, respectively) is still not well studied, but it is relevant to an understanding of the behaviour of structural elements in mylonites. Therefore, the rotation behaviour of rigid inclusions and flow patterns in mylonites are receiving a great deal of attention. Theoretical and experimental studies have focused on five main topics: (i) rotation behaviour of inclusions, (ii) flow patterns in the surrounding matrix, (iii) character of the interface between inclusion and matrix, (iv) flow confinement, and (v) inclusion interaction in densely populated suspensions. In the present work, we focus on the effects of a low-viscosity layer on matrix flow and rotation of isolated rigid inclusions with different shapes and aspect ratio (R).

The rotation behaviour of rigid inclusions in non-slipping contact with an infinite viscous matrix is well studied theoretically and experimentally (e.g., Jeffery, 1922; Muskhelishvili, 1953; Mason and Manley, 1957; Bretherton, 1962; Ghosh and Ramberg, 1976; Freeman, 1985; Passchier, 1987; Ježek et al., 1994; Arbaret et al., 2001; Mandal et al., 2001; Marques and Coelho, 2003; Schmid and Podladchikov, 2003; Schmid and Podladchikov, 2004). Two major conclusions of these works are that (i) all rigid inclusions theoretically rotate continuous and synthetically with the applied simple shear flow (except for inclusions with $R=8$), and (ii) rigid inclusions with $R=1$ rotate synthetically at a constant rate equal to half the far field strain rate ($\dot{\gamma}/2$), independently of shape. The flow in the viscous matrix in non-slipping contact with a rigid inclusion has also been studied experimentally and theoretically for a better understanding of the flow in the Newtonian or non-Newtonian (mostly power law) matrix (e.g., Cox et al., 1968; Masuda and Ando, 1988; Ottino, 1989; ten Brink and Passchier, 1995; Masuda and Mizuno, 1996; Bons et al., 1997; Pennacchioni et al., 2000; Samanta et al., 2002; Samanta et al., 2003; Marques et al., 2005). The results are not consensual as to the relationship between flow type and matrix physical properties, but two main flow types have been described for the non-slipping mode: the so-called eye- and bow tie-shaped flow patterns.

There has been a concentration of research on causes that may alter the rotation behaviour of rigid inclusions and flow patterns around them (e.g., Ghosh and Ramberg, 1976; Marques and Cobbold, 1995; Marques and Coelho, 2001; Biermeier et al., 2001; Marques and Coelho, 2003; Taborda et al., 2004; Samanta et al., 2003), because studies of natural mylonites show that Jeffery's theory for simple shear is not applicable in many natural cases. A possible cause is the nature of the contact between viscous matrix and rigid inclusion. Recent studies Ildefonse and Mancktelow, 1993; Marques and Cobbold, 1995; Bjørnerud and Zhang, 1995; Pennacchioni et al., 2000; Marques and Coelho, 2001; Pennacchioni et al., 2001; Mancktelow et al., 2002; Ceriani et al., 2003; Schmid and Podladchikov, 2003; Marques and Bose, 2004; Schmid and Podladchikov, 2004) have shown that a low-viscosity layer between viscous matrix and rigid inclusion can considerably change the rotation behaviour of the inclusion when compared with the non-slipping mode. Moreover, some argue that this is a real possibility to explain the SPOs found in many natural occurrences of mylonites (e.g. Mancktelow et al., 2002). Marques and Bose (2004) showed with analogue experiments that the flow in the viscous matrix also changes significantly due to a low-viscosity contact with the rigid inclusion. Ice inclusions were used in these experiments, because they slowly melt at the surface during simple shear. The thin layer of liquid water keeps the inclusion in permanent slipping contact with the viscous polymer (PDMS) that was used as matrix. Results regarding inclusion rotation can be found in Table 1.

Taking into account the previous work mentioned above, and following the experimental work of Marques and Bose (2004), we carried out a numerical study with the following objectives: (i) to investigate the effects of a permanent low-viscosity layer on inclusion rotation; (ii) to analyse the effects of inclusion's aspect ratio and shape on its rotation behaviour in slipping mode; and (iii) to investigate the effects of a low-viscosity layer on flow in the