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Analysis of friction influence on material deformation under biaxial compression state

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ABSTRACT

The biaxial compression test, based on the concept presented in [1] and on the technique of the channel-die test [2,3], is discussed as an experimental method allowing evolution of the friction conditions from the dry-film lubrication, by using MoS_2 grease, to the dry conditions to be analysed. This article gives an outline of the experimental set-up, its validation and the technique of the test results analysis. The analysis of friction is based on the experimental data coupled with the numerical simulation of the performed tests and on the theoretical approach introduced in [4]. The Oxygen-Free High Conductivity (OFHC) copper in the '*as-received*' state in contact with the 42CrMo4 steel are chosen as the materials used for the experimental investigation.

1. Introduction

The behaviour of two sliding surfaces in contact with each other has been a matter of interest since, at least, the Renaissance. Indeed, the first written analysis relative to this topic dates back to that time [5] (notebooks and manuscripts by Leonardo da Vinci (1452–1519)). Friction, wear and lubrication (i.e. the general aspects of tribology) were and still are subjects of investigation for ancient and modern engineers, scientists, sportsmen; and are also part of our everyday life. Friction is sometimes of crucial importance (e.g. walking, brakes, materials processing); however, its influence can also have negative effects which can be reduced by the application of lubricants (e.g. metal manufacturing processes).

The influence of friction on the deformation of metals is the subject of extensive studies in many scientific topics covering the fields of wear [6,7], tribology [8,9], mechanics of materials [4,10] or metal forming [11,12], including Severe Plastic Deformation (SPD) techniques [13,14], such as Equal Channel Angular Extrusion (ECAE) [15,16] or High-Pressure Tube Twisting [17,18]. In the above-mentioned fields and many other scientific and industrial applications the direct contact between surfaces at high pressure application leads to a considerable increase in the friction force, which may have undesired effects. Therefore, the understanding of friction behaviour is essential for the design of processes and machines.

The concept of friction can be defined as the resistance to motion of bodies that are in contact with each other [19–21]. The friction force F_μ is a lateral force which must be overcome so that a body in contact with another body can slide over the latter. Coulomb's friction law is the basis for the formally accepted definition for the friction coefficient [22], given here in Eq. (1) [21]. It is suitable for the two regimes of dry friction, i.e. static friction between non-moving surfaces and kinetic friction between moving surfaces:

$$F_\mu = \mu \cdot F_N \quad (1)$$

where F_μ is the friction force acting upon the contact surface, μ is the coefficient of friction and F_N is the force normal to the interface between the sliding bodies.

The dimensionless quantity known as the friction coefficient μ is an empirical property which is material- and system-dependent [23–26]. This statement means the friction coefficient is not only a property of the pair of materials in contact, but that it also depends on the tribological system [24] considered: materials, coating, lubricant, surface roughness, the materials oxidation, relative sliding speed, sliding mode (unidirectional, reciprocating, multidirectional), duty cycle (continuous contact, intermittent contact), environment, temperature, humidity and atmosphere (air, exhaust gases, vacuum) [23–27]. So many factors have an influence on friction in a variety of different, physical situations

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that it makes the task of describing friction complex – the friction behaviour during the described process can be more important than the average value of the friction coefficient. Consequently, tables of constant friction coefficients can be used, assuming that the conditions of the designed process are similar to those under which the values of the friction coefficient are obtained. The practice of using a friction coefficient as a fitting parameter in numerical simulations without deeper reflection is can lead to unreliable calculations.

Generally, a standard experimental approach when examining the sliding friction and static friction coefficients is based on the application of a normal force F_N between two bodies in contact and exerting a tangential force F_μ which allows sliding to occur [23,28]. This methodology is applied in several tribometers used to investigate friction under the conditions of the Severe Plastic Deformation (SPD), e.g. [29–32]. The construction details of the exemplary set-ups are different (in [29] the experiments were conducted by pressing a stationary rider on a rotating disc under high normal pressure, in [32] the set-up was based on the working of a mechanical screw) but the general assumption of friction test, mentioned-above, remains unchanged. The goal of this type of devices [29–32] is to evaluate the static or kinetic friction coefficients in the severe plastic deformation processes, characterised by quasi-static and dry or lubricated sliding conditions during the application of high pressures. One of the experimental observations that resulted from these investigations is that the friction coefficient displays a strong dependence on the normal pressure applied to the bodies in contact. In [31], it was observed that friction coefficient decreased with the increase of the normal pressure and the effect repeated for two sets of surfaces. Purely experimental observations, dedicated especially to friction investigation [29–32], are an important contribution into the domain of tribology. It seems, however, that there is a need for a detailed discussion clarifying the friction behaviour depending on the applied normal loading, based on the obtained experimental results and supported by the analytical and numerical modelling. The authors of the paper presented here would like to add further conclusions concerning the modelling of friction in the biaxial compression test, as this test is carried out under conditions similar to those of the above-mentioned tribological tests.

The biaxial compression test described in this paper is performed by using a cubic specimen placed in a channel-die (the set-up is discussed in detail in Section 2). As friction occurs on four of the six faces of the sample (Figs. 1 and 2), the friction analysis is a crucial issue for the interpretation of the test results. In [4] a discussion is provided on the friction influence during the uniaxial compression test. Knowing the friction correction model for uniaxial compression, the aim is to divide the test into two parts: the initial stage during which uniaxial compression is observed and the final stage when biaxial compression is the dominant process of deformation. The observations and conclusions drawn from it – especially from the friction model built on the inverse method coupling experiment with the numerical analysis – seem to be helpful for the analysis of the results of the above-mentioned tribological tests, e.g. [29–32].

The materials used for the biaxial compression test: the Oxygen-Free High Conductivity (OFHC) copper in the 'as-received' state [33,34] in contact with the high-strength 42CrMo4 steel [35,36], are described in Section 2. During the experiment, MoS_2 grease [37], a dry-film lubricant, was used to minimise friction.

The details of the experimental set-up are reported in Section 2. The numerical simulations of the biaxial compression test, which lead to the friction analysis, are discussed in Section 3. The analytical model based on the inverse method, coupling the experiment with the numerical simulation, is introduced in Section 4. Section 5 consists of the final conclusions.

2. Biaxial compression in a channel die

The biaxial compression test is based on the concept of the channel-die compression test [2]. An improved channel-die set-up was designed and adopted providing a remarkably uniform deformation [3]. By means of the channel-die compression test it is possible to induce a plane strain in most of the volume of the material. Recently, the channel-die technique has been used to

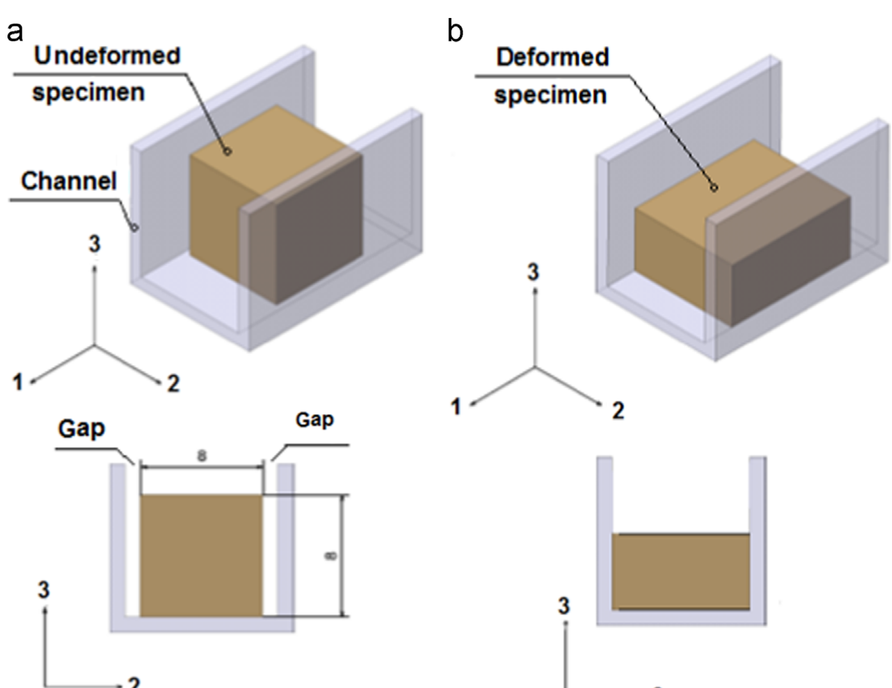

Fig. 1. Schematic description of the biaxial compression test using a channel die. (a) Before loading, initial stage and (b) after loading, final stage.