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Short communication

Wear mechanisms of diamond-containing hardmetals in comparison with diamond-based materials

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ABSTRACT

The abrasion resistance of diamond/WC based hardmetal composites (commonly referred to as "diamond enhanced carbide", or "DEC") has been evaluated relative to those of a group of more conventional WC-Co materials and diamond (both polycrystalline and CVD) materials. Abrasion resistance, evaluated by means of the widely reported ASTM B611 test, was complimented by simulated field drilling trials, using a fine-grain quartzite, in the laboratory. This approach was taken as the drill test format has wider acceptance than another (complimentary) laboratory test, whether standardised, or bespoke, amongst end-users. In abrasion tests, polycrystalline and CVD diamond materials performed best, with the DEC materials being on a par with their conventional WC-Co counterparts. This behaviour was explained by the fact that the diamond in the composite (DEC) materials was readily plucked out of the wear surface, due to the aggressive nature of the B611 test. However, percussive drilling tests proved more encouraging, as the extent of diamond pluckout in DEC was not as widespread as in ASTM B611. Also, on the drill bit DEC insert surface, rock fragments were found to adhere to it, which appeared to have mitigated the severity of the prevailing wear regime somewhat.

1. Introduction

The work reported herein is a joint collaboration between Element Six personnel in the UK and Germany, bringing together expertise in tribology (abrasion) and materials formulation/application.

The paper deals with conventional wear laboratory tests, whose format was selected on the basis that it represents more closely than the suite of candidate standardised tests. Work reported in this technical field usually reports either on laboratory tests, or on field tests. However, this paper attempts to reconcile the two, by combining both approaches. Initial laboratory tests were combined with percussive drill tests, which were conducted under parameters chosen to simulate actual mine operations as closely as possible.

Tungsten carbide (WC) based hardmetal was first synthesised (it does not occur in Nature) almost 100 years ago by Osram [1]. It is widely used both as a wear resistant component or a cutting tool in a number of high added value applications, under which the operating regimes can be very arduous, with any combination of high contact stresses, cyclic [2], or percussive/rotary-percussive loading [3], or corrosive/tribo-corrosive environments predominating [4,5]. The WC-based hardmetal material genre is a well-established and proven one, whose fundamental physical properties (hardness and fracture toughness) can be tailored according to end-use by selection of WC grain size, binder volume fraction, and choice of binder (cobalt and/or nickel for the greater part) [6].

Tool material developments in the offshore mineral extraction industries and in mining are predominantly cost-driven. Common *leitmotifs* are the winning of reserves; e.g. directional drilling [7] for oil and longwall mining [8], now being extended from coal, where it is well established [9], and increasingly into other minerals [10]. Component life extension is one of the key outcomes which the relevant industries desire from applied materials R&D. Complimentary to this is the minimisation of down-time; pillar and stall (room and pillar) mining, with its requisite downtime after shot blasting is a prime example. Another aspect of material behaviour which the industries seek to minimise is premature failure. For example, in highway resurfacing, premature failure of picks on a road planer has the potential to undo prior contractual arrangements for the use of costly hardware. Even in deepcast coal mining, where longwall shearing predominates as the means of coalface advancement [9], premature tool failure can occur from encountering a hard igneous intrusion in a seam [11].

The demands on material performance have led to the introduction

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of diamond-based or diamond-enhanced tool compositions and designs into the aforementioned applications. This family of materials come in various formats; CVD diamond on a hardmetal substrate [12], PCD outer layers put down sequentially on a tool, or particulate diamond co-sintered + HIPed with hardmetal [13].

There is a trend in the research on hard and superhard materials to produce WC/Co-diamond composites by adding diamond grains to WC-Co powder mixtures and their sintering at low pressures and moderate temperatures for short times (see e.g. [14,15].). There are considerable technological difficulties related to the fabrication of such diamond-hardmetal composites at low pressure, as diamond is thermodynamically unstable at low pressures and can therefore easily graphitize during sintering. Nevertheless, it has not been established on a definitive basis whether such hardmetal-diamond composites can demonstrate wear-resistance and lifetimes significantly exceeding those of WC-Co hardmetals, particularly nanostructured or so-called "near-nano" hardmetals with WC mean grain size of below 0.2 μm.

The major objective of the present work was to produce WC-Co-diamond materials at high temperatures and ultra-high pressures, at which diamond is thermodynamically stable, examine their wear- and impact resistance in comparison with different WC-Co and diamond-based materials and evaluate wear mechanisms of the materials in wear tests of two different types.

2. Materials

Materials reported in this study include conventional WC/Co hardmetals, WC/Co hardmetals with addition of diamond ("diamond enhanced carbide"; hereafter referred to as "DEC"), and polycrystalline diamond (PCD). The latter two material genres are finding increasing favour in the most arduous applications in the extractive industries [13,16] and in highway construction and/or renewal [17]. DEC and PCD can be introduced as the actual tool face to promote tool life [18,19]. A combination of FEA [20], laboratory testing [21] and field trial feedback [22] has accumulated sufficient knowledge to decide on tool material composition and tool geometry with a degree of confidence. However, as reported by Boland and Li [16], DEC does not always produce the predicted superior performance (a wide variation in wear resistance was found in an apparently similar family of materials), which is principally a case of tailoring the microstructure for a particular end-use and/or operating conditions.

3. Test format

The ASTM B611 wear procedure [23] is a test, which though simple in concept (schematically shown in Fig. 1), finds applicability as an effective benchmarking tool for evaluating the response of a range of hard engineering materials to high stress abrasion [24]. Though the test configuration (see Fig. 1) and operation are detailed in the standard [23] and in reference papers [24,25], it is timely to briefly recall its basis.

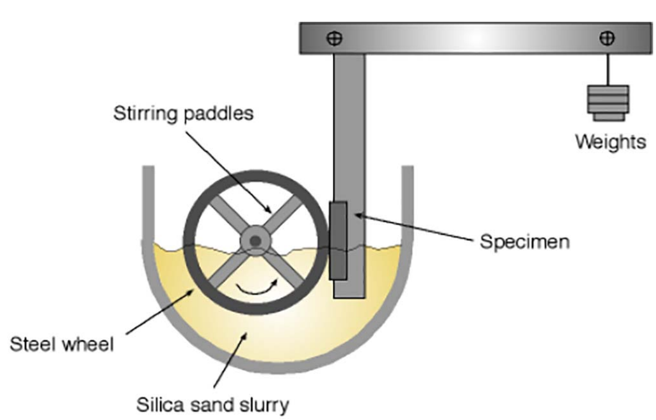

Fig. 1. Schematic of the ASTM B611 test format.

The test consists of a vertically-held flat rectangular test sample, nominally of dimensions 40 × 20 × 5 mm (though the jig does allow for tolerance in this respect; the sample being located in the jig with hexagonal head screws, which also allow fine tuning of its position relative to the counterface), held in place by a deadweight lever arm against a cast iron wheel of prescribed dimensions. The cast iron wheel features S-shaped ribs on its sides. The wheel is located in a bath of an aqueous brown alumina slurry of prescribed composition [23]. Upon test commencement, the wheel rotates against the vertically held flat sample, and the S-shaped side ribs on the wheel act to stir up the slurry, enabling slurry to be drawn into the interface between wheel and flat, thus producing an abrasive stream. The S-shaped ribs are a key feature of the apparatus; not only do they promote abrasive entrainment into the contact area, but also serve to agitate the slurry, thus promoting its recirculation; in this respect they are effectively "stirring paddles", as denoted in Fig. 1.

The test format finds significant utility and popularity in the oil & gas and mining industries; it is a test which uses a hard counterface, unlike ASTM G65 which uses a compliant one, and produces a significant, measurable wear loss in an acceptable time frame. Amongst hard materials, ASTM B611 [23] has found particular favour with tungsten carbide-based hardmetals [24]. In this material genre, results are produced with minimum scatter for a given composition and/or properties [25,26]. With respect to the former, this is of especial importance, as choosing the optimum hardmetal grade for a particular oil, gas, civil engineering, or mining application for a given tool geometry/configuration can have a significant impact on tool life. ASTM B611 produces wear in hardmetal, to the greater extent, by micro-fracture; the localised manifestation of a severe abrasion regime. Of all (standardised) laboratory tests, this simulates most closely the wear modes (neglecting chipping or gross premature component failure by macro-fracture) seen in components such as drills, hammers and picks. The key differences between laboratory test and application are in the nature of the abrasive/counterface, applicability of thermal transients [27] and also in the dynamic response of the test system vs that in the field application [28]. In this respect, the counterface could be rock (iron ore [29], granite [30], gypsum [31], limestone/chalk [32], coal [33], or in the case of a road pick; concrete [34] or asphalt [17]). In the field, the distinction between counterface and abrasive can be somewhat academic. Despite the use of rock counterfaces in laboratory tests [35], or rock styli [36], to give more credence to the laboratory data by simulating conditions a little more closely aligned to those in the field, standard test data are still widely referred to, applied, and generated. Though the rock counterface test may be able to show how the rock interacts with the tool on a microscopic basis, there can be pitfalls in some scenarios; for instance if a granite indenter is used as the counterface in a traversing scratch test (i.e. a model two-body abrasion scenario [37]), the actual material at the contacting apex could be any one or more of the macro-constituents of a granite; namely mica, feldspar or hornblende, unless carefully controlled, as by Olsson et al., in ref. [36].

Complimentary to the laboratory abrasion tests, laboratory performance tests on percussive drilling were also conducted. In this case the counterface (the material being drilled) is a fine-grain quartzite [38], of ultimate compressive strength ~26 MPa. This particular rock was selected for its high degree of abrasivity (an order of magnitude higher than granite under percussive drilling conditions). The setup, showing an overall view, and also a close-ups of the face being drilled are shown in Fig. 2a–c respectively. The percussive drilling tests were performed using the hardmetal-diamond composite comprising a relatively low proportion of diamond (30% diamond) in comparison with that employed for the wear tests (42% and 69% diamond), as the hardmetal-diamond inserts containing more that 30% diamond had premature