Int. Journal of Refractory Metals & Hard Materials 27 (2009) 332–343

Contents lists available at ScienceDirect

Int. Journal of Refractory Metals & Hard Materials

journal homepage: www.elsevier.com/locate/IJRMHM

Structure–property relationships in liquid jet erosion of tungsten carbide hardmetals

A.J. Gant *, M.G. Gee

National Physical Laboratory, 12D, Hampton Road, Teddington, Middlesex TW11 0LW, UK

ARTICLE INFO

Article history:
Received 26 August 2008
Accepted 23 November 2008

Keywords:
Tungsten carbide
Hardmetal
Erosion

ABSTRACT

The National Physical Laboratory has recently commissioned a liquid jet erosion rig capable of infinitely variable impingement velocities and slurry erodent volume fractions. Initial work using the new tribometer is being focussed on hardmetals based on tungsten carbide, either with a cobalt binder or cobalt/nickel binder. Investigations have been conducted into correlating wear behaviour with conventional parameters used for characterising hardmetals (hardness, binder linear intercept and WC grain size) and also the relative contributions of ductile and brittle response to the impinging slurry. Electron microscopy has been used to relate quantitative material loss due to erosion with prevailing wear mode(s) and to clarify structure–property relationships. The WC based hardmetals show an inverse log–linear relationship between hardness and volume loss, but with microstructural determinants also factoring in. Brittle fracture of WC grains and pluckout (undermining) is seen on wear surfaces. Erosive material loss correlated with WC grain linear intercept for a fixed binder content. In general, using an impingement angle of 45° (as opposed to a normal incidence stream) induced less volume loss and often a milder wear regime could be seen to be operative under these conditions.

1. Introduction

Liquid jet erosion and liquid jet erosion–corrosion are techniques which are relevant to a wide range of industries using a range of liquids, erodents and component materials. Work has recently been reported [1] in which the operating characteristics of a liquid jet erosion rig at the National Physical Laboratory (NPL) have been assessed. The longer term aim is to thoroughly characterise the erosion behaviour of a range of tungsten carbide based hardmetals supplied to the National Physical Laboratory from constituent members of the British Hardmetal Research Group (BH RG). Erosion behaviour of hardmetals is important to understand as it can aid in the tailoring of hardmetal compositions for particular applications, such as choke valves used in offshore oil extraction.

The erosion behaviour of WC/Co hardmetals, despite its industrial importance, has not been as widely reported the as the response of these materials to abrasion wear. In terms of experimental procedure, material response to testing and test rig configurations, abrasion is relatively straightforward and the interpretation of material behaviour, though non-trivial, can be readily understood in terms of mechanical properties alone; principally hardness [2–4], though toughness is also important. The characteristic high hardness and fracture toughness of WC/Co hardmetals [5–7] has made them the optimum material for use in such harsh environments as cutting tools, mining bits, choke valves, sandblasting and coal slurry nozzles. WC/Co hardmetals are comprised of a hard, brittle WC phase with ductile metallic phase (i.e., the "binder"). The metal is normally cobalt, but there are other binder phase materials such as nickel, cobalt/nickel chosen for other properties such as corrosion resistance. This generic family of materials perhaps owes both its wide applicability and commercial success due to the fact that its properties can be tailored according to those required in a particular component [8,9]. Principally, WC grain size and cobalt content can be varied (independently) to produce the requisite hardness and toughness (and/or the combination of these two parameters). WC/Co is also commonly described in terms of the scale of its microstructure; often the WC grain mean linear intercept (d_{WC}) and the binder mean free path (λ_{Co}) [10,11]. Structure–property relationships in hardmetals (principally between WC grain size, binder mean free path and hardness) are well-documented in the literature [12–14].

The response of WC hardmetals to a fluid jet with particle entrainment is far from straightforward. Materials which are brittle in the "classical" sense such as glasses and a range of technical ceramics have been the subject of a number of studies looking at the response to single particle impacts in terms of fracture, which can be lateral, cone and median cracks and models have been produced which describe such materials' response as quasi-static or dynamic impact [15,16]. By contrast, WC/Co hardmetals do not always behave in a classical brittle manner when subjected to an erosive fluid jet; at least on the microscopic scale. At this

* Corresponding author. Tel.: +44 20 8943 6802; fax: +44 (0) 20 8943 2989.
E-mail address: Andrew.gant@npl.co.uk (A.J. Gant).

0263-4368/$ - see front matter Crown Copyright © 2008 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijrmhm.2008.11.013

scale they can sometimes behave in a ductile manner, or display some attributes of both ductile and brittle behaviour. The combination of test conditions and material properties/microstructure determine the response of a particular WC/Co hardmetal to a liquid jet; the severity of erosion and whether erosion is primarily brittle or ductile in nature [17]. Factors determining the severity of erosion are principally jet velocity (high velocities produce more severe wear), high impingement angles (90° or approaching normal incidence). Also, the nature of the erodent itself is a determinant as to whether severe erosion (characterised by a ductile response) or a mild erosion regime will prevail (characterised by a brittle response); in short, large particle sizes, high particle hardness and also angularity will promote severe wear.

2. Experimental

2.1. Test apparatus

A typical test system is shown in Fig. 1. The set-up (shown schematically in Fig. 2) consists essentially of a closed loop flow system powered by means of a vertically mounted progressive cavity pump. Uptake and circulation of sand is enabled by appropriate choice of pump speed; the flow round the bypass circuit (described in the following paragraph) causes sufficient turbulence to prevent sand settling out in the tank. Jet velocity is determined by chamber pressure (for a set nozzle diameter), which in turn is controlled both by pump speed and bypass valve adjustment. The rig has been designed with a certain amount of flexibility with regard to sample positioning under the liquid jet; both the stand-off distance and effective incident angle can be varied.

Essentially the rig consists of an inlet annular orifice (A) which acts as the system intake for the erodent/liquid mix. The mix is taken up the vertical tube above A by the action of the integral pump/motor and delivered into a chamber (C). The mix is then taken up and round the outlet pipework to E and into a sump tank for recirculation and also down a 5 mm vertical tube which forms the jet impinging on a sample carousel suspended at D. Pump rotational speed and chamber C pressure can be controlled independently. Chamber C pressure can be controlled manually via a pneumatically operated valve which in turn governs the proportion of liquid/erodent mix bypassing the impingement jet via E. Photographs of key components of the rig are shown in Figs. 3 and 4.

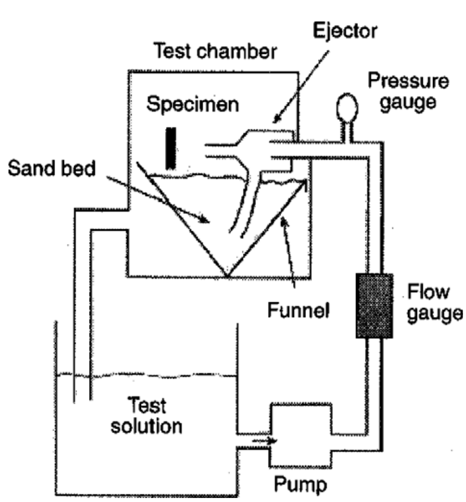

Fig. 1. Typical liquid jet test system.

2.2. Materials

Constituent members of the British Hardmetal Research Group (BH RG) supplied a range of WC hardmetal samples (as detailed in Table 1), of dimensions 50 × 50 × 5 mm. The samples were surface ground using a resin-bonded grinding wheel of 165 μm diamond grit to produce flat, parallel faces. This surface preparation was chosen as it is widely used in the hardmetal industry. The samples were then annealed for one hour at a temperature of 800 °C to remove residual stresses induced by surface grinding. Components such a choke valve trims which are subjected to liquid/slurry erosion streams are not commonly annealed, but the depth of material removal over the lifetime of a choke trim is expected to be far greater than in the current laboratory test regime. With this in mind, surface and/or subsurface residual stresses induced by grinding is a variable which is undesirable and given the relatively shallow depth of erosion produced in the laboratory tests (50–100 μm), a not inconsiderable proportion of the depth eroded would be residually stressed from grinding. In short, although it is acknowledged that annealing is not common in industry, annealed material is more representative of component material conditions when the component is operating *in situ* [1]. In all, nine batches of specimens were tested, with five specimens of a given specification being tested under any one test condition.

2.3. Test regime

Erosion tests were carried out using a slurry of rounded silica sand (mesh size range 60/85), supplied by David Ball plc, Barr Hill, Cambridge, England, and water of pH 6.3. Erosive wear testing was carried out with the rig pump running at 240 rpm and the flow governed by the bypass valve so as to give an indicated pressure of 4 bar. Prior to sample testing commencing, the tank was filled with 120 l of sand/water slurry; the volume fraction of sand to water being 1:10. The sand/water mix was then allowed to settle in the tank and then an amount of water (approximately 10 l) was then extracted from the holding tank and the rig primed by pouring this water through a filler cap. The pump was then started and run up to its operating speed of 240 rpm, then the chamber was pressurised to 4 bar indicated pressure by adjusting the bypass flow valve (operated by compressed air). Under such conditions, the sand in the holding tank was agitated sufficiently to enable the pump to entrain the sand, producing a volume fraction of 25% sand in the nozzle stream. The volume fraction used was chosen as being representative of a subsea oil well in midlife; during early stages of well operation sand entrainment is negligible and towards the end of life, well streams can be mostly entrained sand. Five minutes were allowed to achieve steady state conditions for sand agitation, entrainment and delivery through the nozzle; commissioning trials showed that 5 min was adequate to achieve repeatable sand delivery through the nozzle [1]. Under these operating conditions, a nozzle jet velocity of 19.9 m s^{-1} was achieved. Emerging jet velocity was measured by timing aliquots of sand slurry; slurry was collected in a calibrated vessel over a fixed duration (measured by a calibrated stopwatch) and given that nozzle diameter was known, jet velocity could be calculated easily. Impingement angles of 45° and 90° were used. Nozzle internal diameter was 5 mm and nozzle vertical displacement from the specimen target surface was 25 mm. The nozzle was 300 mm long and made of fine grain 95% alumina (5% glassy phase). Periodic checks on nozzle wear were made using a calibrated vernier calliper to measure the internal diameter in four orientations (0°, 45°, 90° and 120°); no wear was detected during the course of the tests reported herein.

Hardmetal mechanical properties measured were Vickers hardness HV_{30} and Palmqvist toughness (WK_{30}). Microstructural data