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Wear modes in slurry jet erosion of tungsten carbide hardmetals: Their relationship with microstructure and mechanical properties

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ABSTRACT

Hardmetals based on tungsten carbide (either with a cobalt binder or cobalt/nickel binder) have been subjected to slurry jet erosion, using silica sand or alumina erodent entrained in a water jet. Wear processes have been identified in a number of hardmetals and results correlated with conventional parameters used for assessing hardmetals (hardness, binder linear intercept, WC grain size). Results were obtained using two principal impingement angles; normal incidence (90°) and 45°, and were correlated with bulk hardness but the relationships that were found differed in detail from those for abrasion. Local microstructure, evidenced by electron microscopy on wear scars and cross-sections, appears to play a more fundamental role in the respect of material response to erodent impact, with WC grain size being a major determinant. The type of erodent used had a significant effect on material response; microscopic plastic grooving occurred readily with an alumina slurry jet, but was not evident in the case of silica sand. 3-D spatial analysis via a confocal optical microscope and also a non-contact scanning eddy current probe of wear scars have also used to characterise their shape and extent of degradation respectively.

1. Introduction

Slurry jet erosion and slurry jet erosion–corrosion are two laboratory-based test regimes which have a bearing on multifarious applications in which hardmetals (and of course other generic material types) are subjected to severe operating demands. Enhanced knowledge of hardmetals' response to erosive service conditions is key to the intelligent design of hardmetal compositions for particular end uses, such as the winning of offshore hydrocarbon fields, mining and process industries.

Erosion of tungsten carbide based hardmetals has received relatively little coverage in the literature relative to abrasion despite its prominence as an industrial degradation mode. Abrasion resistance, despite being a material response that can never be entirely divorced from the test system employed to characterise it, is seen in hardmetals to be essentially governed by hardness, and related to microstructure by a pseudo Hall–Petch relationship [1–4], though fracture toughness also has a role to play in the more brittle material variants. The combination of high hardness and yet a range of fracture toughnesses comparable with tool steels rather than technical ceramics [5–7] has made WC/Co hardmetals the preferred material choice for use in a multitude of heavy duty wear and tribo-corrosion scenarios; their wide applicability and commercial success due at least in part to their microstructure (WC grain size, binder mean free path) or properties (hardness and toughness) being tailored according to those required in a particular application [8–14].

Hardmetals in general respond to particulate erosion in a fashion which can be seen to a composite behaviour; they exhibit some features which are akin to those seen in microscopically brittle materials such as glasses and technical ceramics, yet also exhibit ductility; both in the metallic binder and in the WC grains themselves (accounting for minimum erosion resistance at impingement angles somewhat less than 90° for most compositions and operating conditions; unlike glasses and technical ceramics, where this does occur at normal incidence). The response of glasses and technical ceramics to model single impact experiments has given rise to the modelling of their response as either quasi-static or dynamic impact on the basis of the particular surface/sub-surface crack system produced [15,16]. Although hardmetals do not in general produce the above response, having a significant ductile component [17,18], the models will be taken as a starting point in the present study to further understanding of their behaviour.

2. Experimental

The test system used at NPL is shown schematically in Fig. 1; the technical details have previously been reported by the authors [1]. Essentially a hardmetal sample is held at a prescribed standoff distance and impingement angle from the slurry jet; the latter being forced down a 5 mm internal diameter alumina tube, impinging on the hardmetal sample at a velocity of 19.9 ms^{-1}.

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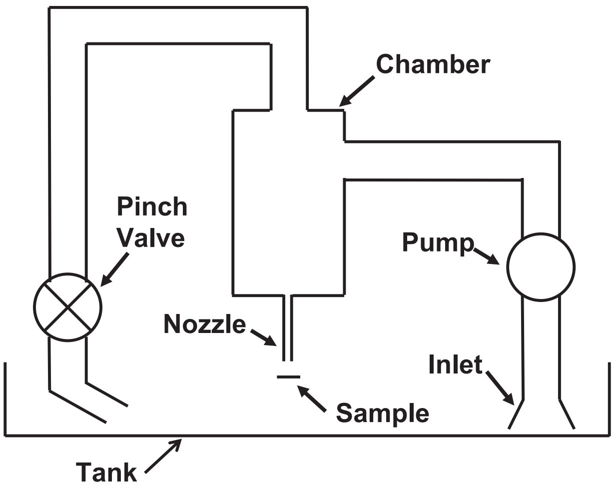

Fig. 1. Schematic of NPL liquid jet test system. NB: Not to scale.

2.1. Materials

Constituent members of the British Hardmetal Research Group (BH RG) supplied a range of WC hardmetal samples (as detailed in Table 1), ground to dimensions of 50 × 50 × 5 mm. The samples were annealed at NPL for 1 h in vacuo at 800 °C in order to eliminate surface residual stresses as far as practicable. Although 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.

2.2. Test regime

Erosion wear trials were undertaken with a volume fraction of 25% round silica sand (212–300 μm size) in the nozzle stream with pH 6.3 mains water as the carrier medium; chosen as being representative of a mature subsea oil wellstream. An initial five minute period for sand agitation, entrainment and delivery transients to achieve steady state was found adequate to achieve repeatable sand delivery through the 300 mm long nozzle [1] at a jet velocity of 19.9 ms^{-1}, using a 25 mm standoff distance, with 45° and 90° sample impingement angles. After the initial five minute period, the sample holder was swung into position under the emergent jet at a preset impingement angle for a standard 20 minute duration. Regular nozzle inspections (visual inspection and diametrical checks with a Vernier micrometer) did not reveal any perceptible wear during the current study.

Hardmetal mechanical properties and microstructures were thoroughly characterised in-house at NPL and are shown in Table 1. Note that Palmqvist toughness measurements had to be conducted with a 100 kgf load to generate cracks in the whole suite of samples. Commonly used lower loads (30 and 50 kgf) would not induce fracture in the coarser grained materials. Microstructural measurements in Table 1 were produced from SEM images, with 500 WC grain and 500 binder intercepts being measured in each grade. The contiguity and standard deviations were produced therefrom. WC/WC contiguity ("C") was calculated from the microstructural measurements:

$$C = 2(N_L)_{WC/WC}\left[2(N_L)_{WC/WC} + (N_L)_{W/Co}\right] \quad (1)$$

Scanning electron microscopy was undertaken on wear surfaces using a Zeiss Supra field emission scanning electron microscope (FESEM) in direct electron mode (SEI); the majority of samples being as-tested erosion scars.

Two grades of WC hardmetal, NK07 and mars11A were subjected to further study; samples were polished using established semi-automatic metallographic procedures (finishing with 0.25 μm diamond) and then subjected to the same erosion regime as the samples in the main testing programme. This was for the specific purpose of wear surface microscopy; endeavouring to gain knowledge of the material removal mode(s) that were operating. The eroded samples were sectioned vertically through the wear scars (produced by both impingement angles) using a diamond cut-off wheel and were then embedded, ground on diamond discs and metallographically polished to a 0.25 μm finish, whilst preserving edge retention in the polished surfaces using selected mounting media and metallographic preparation routes. Erosion was carried out on polished surfaces as opposed to the more usual diamond ground surfaces to eliminate any confusion between genuine wear features and spurious surface and/or sub-surface features from the grinding process.

Additional NK07 and mars11A samples were eroded with F60 grade brown alumina grit using the same test regime used in conjunction with the alumina was identical in every detail as for the silica sand in terms of surface finish, exposure duration, impingement angles, erodent volume fraction and nozzle jet velocity. The purpose of the exercise was to conduct a parallel study into erosion mechanisms with a different erodent species of similar grit size, though whose hardness, angularity and tendency to undergo communition are radically different from rounded silica sand.

Table 1
Hardmetal inventory and properties; percentage wt. binder, mean binder linear intercept, WC grain mean linear intercept, 30 kgf Vickers hardness, plane strain fracture toughness (K_{IC}) and Palmqvist toughness using a 100 kgf load (WK100).

Grade	wt.% binder	d_{Co}, μm	SD d_{Co}, μm	SD d_{WC}, μm	d_{WC}, μm	Contiguity
mars6C	6	0.61	0.46	0.84	2.07	0.72
NK07	7% Ni/Co	0.13	0.06	0.14	0.26	0.75
shmcn5	5	0.18	0.13	0.16	0.25	0.39
shmcn12	12	0.16	0.10	0.22	0.25	0.62
mars6ANi	6% Ni	0.29	0.16	0.37	0.63	0.55
marsl 1A	11	0.56	0.35	0.42	0.86	0.46
mars 11 D	11	1.00	0.71	1.04	1.90	0.42
mars6B	6	0.56	0.34	1.13	1.11	0.70
mars6E	6	1.20	0.76	2.21	6.42	0.58
shm220	6	0.08	0.05	0.12	0.17	0.78
mars 11 E	11	1.98	1.49	2.47	4.04	0.51
mars6A	6	0.21	0.22	0.40	0.67	0.64
macn9	9	0.18	0.10	0.17	0.32	0.59

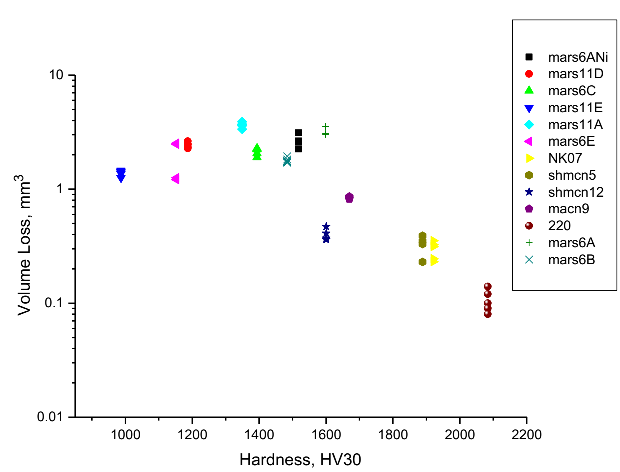

Fig. 2. Volume loss vs hardness for 20 minute erosion tests with 45° impingement angle.