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Mapping of impact-abrasive wear performance of WC–Co cemented carbides

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ABSTRACT

A reliable evaluation of the wear resistance of materials used in conditions of combined impact and abrasion is of a paramount importance for industrial applications. A new tribo-device for studying impact-abrasive wear performance of materials was worked out. The specimen is pressed against a rotating steel wheel with abrasive being fed by gravity between them. The generator is supplying the tribosystem with impacts of predefined energy in a range of 0–19 J and a frequency up to 55 Hz. Cemented carbides of different binder content (6, 8, and 15 wt%) and carbide grain size (fine, medium, and coarse) were tested for impact-abrasive wear resistance. Maps reflecting the performance of cemented carbides at low and medium stress abrasion as well as medium stress abrasion combined with impact are constructed. The maps assessing the effects of stress intensity, dynamic loading, and combined effect of increase in stress and application of the dynamic load are thoroughly discussed. Microstructural analysis of the wear mechanisms is performed to support the conclusions.

1. Introduction

The exceptional performance of WC–Co cemented carbide (hardmetal) in many tribological conditions is due to combination of high hardness of the tungsten carbide particles, high fracture toughness of the cobalt binder and strong adhesion between phases [1–4]. There is a huge amount of parameters influencing wear behaviour of cemented carbides; therefore, the mapping of their performance in specific tribo-conditions is still a challenge. For example, properties of the hardmetals are highly dependent on the method and conditions of manufacturing as well as on chemical composition and developed microstructure [1–8]. Increasing the binder content until the optimum value in cemented carbide usually results in increased wear resistance in conditions of dynamic loading [1–13]. It is a well established fact, that the energy dissipated during the wear process can be transferred into the formation of the surface layer with improved wear resistance [14–20]. Hardmetals with medium and high binder content (>5 wt%) easily adapt to the wear conditions due to possible shifting or re-embedding of ceramic grains and the availability of a spaces between grains that may be additionally reinforced by products of wear process, which leads to the formation of a mechanically mixed surface layer (MML) [19–23]. Under the dynamic conditions, the binder metal from the subsurface layer is squeezed towards the surface, resulting in a rearrangement of WC grains and the reduction of the mean free path in the subsurface layer [5,24,25]. An excessive (>20 wt%) binder content results in high abrasive wear rates due to the facilitated access of the fine abrasive particles [19,20].

Cemented carbides with fine ceramic grains usually have higher hardness, compressive and fatigue strength but lower fracture toughness [9–12] compared to coarse grained composites. Fine size of the carbide grains is favourable prevention of wear by the large abrasive particles; however, if the abrasive particles are subjected to intensive fracturing the fine grained hardmetals lose their advantages and experience quite high wear rates [26–28].

Tungsten monocarbide (WC) grains have a lower hardness than that of fused two-phase (W_2C+WC) carbide grains but have higher fracture toughness, and are more resistant to high temperature dissolution and formation of eta phase, although they exhibit a higher cost [29,30]. The content of carbon in the precursor mixture of powders and the parameters of sintering (atmosphere, temperature, duration, heating, cooling rates, pressure, etc.) should be set very precisely to avoid the formation of brittle eta phases or free carbon acting as stress concentrator [31].

The depth of the layer affected by the wear can be as thick as 10 carbide grains depending on the intensity of the wear, but major changes are usually observed within the layer of a thickness equal to the size of 3 carbide grains [19,20]. The increase in local stresses

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(higher energy of impact) usually results in a threshold where the rate of material removal rises significantly, due to a change in the wear mechanism which may be classified as a transition between high and low cycle wear [6]. The high cycle wear mechanism is always preferred since the development of cracks or other damage features takes more time and results in lower wear rates [11,23,32].

In addition to residual mechanical and thermal stresses resulting from the milling and sintering processes experienced during production, stresses induced by the wear influence the performance of the final products. After sintering, WC grains are kept in compression (the thermal expansion coefficient of Co is higher than that of WC) which improves the performance of the WC grains [1–4]. Local heating of contact points (flash temperature) during wear with temperatures reaching 2000 °C may lead to melting of the binder and changed thermal stress states [6,11]. Coarse grained cemented carbides of high binder content have a higher thermal conductivity, which reduces thermal gradients [11,33–35]. The tribolayer composed of original phases (binder and ceramic grains) and products of wear process having usually fine size that are mechanically introduced and mixed has a lower thermal conductivity compared to untreated hardmetals, due to the large number of interfaces [33–36].

The variation of properties within final products made by the powder metallurgy route inevitable due to the variation of stresses experienced by the green body during compaction may be partially solved by hot isostatic pressing [2,12,37]. New binder materials to substitute cobalt are studied to make Co-free corrosion resistant materials suitable for elevated temperatures [8].

Therefore, optimisation of the products for applications requiring sufficient abrasive and impact tolerance is a challenging and complicated task. Depending on the severity of the tribological contact, the materials with the optimum combinations of properties and microstructural features have to be carefully tested and selected [23,38,39]. Laboratory testing provides faster, better controlled, and less expensive testing than field tests [40,41].

There are many applications where materials are working in combined abrasive and impact conditions (drill bits, crushers, picks for road maintenance, car wheel studs, snow plough blades, etc.), while the types of laboratory equipment suitable for this type of testing is very limited. In high-energy milling type of tribo-devices (disintegrator), the resistance of materials against the impact of abrasive particles (up to 10 mm) can mainly be studied [42]. The energy of the impact in an impeller type tester [43,44] depends on the size of the abrasive particles and the impeller velocity. The adjustment of the force between the sample and the abrasive for the device described in [45] (pin against cylinder filled with abrasive) is complicated. Both devices suffer from the deterioration of abradant which results in change of wear conditions during the test. A device (plunger against the plate with abrasive between) described in [46] has a low energy of impact (0.8 J) and a low frequency (2 Hz), and is suitable mostly for short tests at high temperatures due to the deterioration of the plunger. A device presented in [47] has a quite high impact energy (up to 5 J), with a low impact frequency (1.7 Hz). It does not allow abrasive testing without impacts. The fixation of the specimen for this and for the impeller type of devices is hardly suitable for hardmetals (the sample should have a hole) [43,47]. The test with a sample pressed against rock while abrasive is fed in between, as described in [48] has no dynamic loading. None of these devices have the option to study the effect of inertia of the loading system which may result in significant changes in the wear mechanism and wear rate [49]. Testing of extremely hard materials such as binderless WC ceramics, WC/diamond composites [50] or polycrystalline diamond by simplified scratching or scratching accompanied by impacts [51] is complicated due to the absence of indenters having sufficiently high hardness (higher than that of the materials under investigation), which is required for reliable testing. These materials have extremely high resistance against abrasion; however, they may experience a catastrophic brittle fracture during impact loading.

Wear rate graphs of cemented carbides are available and illustrate the general trends [9–12,21,23,41,52,53]. In paper [23] the most often used grades with 5–15 wt% Co content were omitted and the wear data were absent. The maps that simplify the selection and provide a better understanding of cemented carbides behaviour under the studied set of parameters have been quite limited up to now [40,54–60]. Maps showing wear performance of cermets, hardmetals and metal matrix composites in aqueous conditions are presented in [54–56]; wear maps for dry and lubricated sliding of steels and ceramics are given in [40,57,58]; the approach for construction of maps in erosive and abrasive conditions of brittle materials may be found in [59,60]. The aims of the current study are: to build the maps showing the wear rates of the cemented carbides in low stress, medium stress and medium stress with impact conditions; and to map the wear rate variation of materials due to changes in loading conditions.

2. Materials and methods

2.1. Materials

The WC–Co cemented carbides with varied WC grain size and cobalt content were produced by a conventional PM routine at Tallinn University of Technology, Laboratory of Powder Metallurgy. All powders were commercially sourced and the description is provided in Table 1.

Sintering was performed by hot isostatic pressing (HIP) at different temperatures depending on the cobalt content: 1390 °C (15 wt% Co) and 1450 °C (6 wt% or 8 wt% Co). The properties of the conventional cemented carbides had been intensively studied [1–12,21,23,38,52,53] and are not provided here. The nomenclature of the hardmetal grades follows the designation of WC grain size (fine, medium, and coarse). The carbide grains size of sintered samples determined by linear intercept method (BS EN ISO 643:2012) was within the range of 0.2–1.0, 0.5–2.0 and 2.0–10.0 μm for fine, medium, and coarse hardmetals respectively. Bulk alumina (Al_2O_3) and wear resistant alloy Hardox 400 [61] were tested along with the cemented carbides for comparison between ceramic, ceramic–metallic, and metallic materials.

2.2. Methods

The multifunctional modular tribosystem (MMTS) in configuration C1 was applied for testing of materials in low stress abrasive conditions according to ASTM G65 standard [28] (Table 2).

Table 1
Description of powders used for production of cemented carbides.

Designation	Size (μm)	Supplier	Purity (%)	Grade
Fine WC	0.1	H.C. Starck	99.0	DN-4.0
Medium WC	0.9	Wolfram Bergbau und Hütten AG	99.0	CRC 030-40
Coarse WC	10.0	H.C. Starck	99.0	HC 1000
Cobalt	0.3	Pobedit (Russia)	99.3	PK-1Y, GOST 9721-79