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Fatigue performance improvement of electrical discharge machined hardmetals by means of combined thermal annealing and surface modification routes

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ABSTRACT

Electrical discharge machining (EDM) provides an effective means of shaping hardmetals. However, it is also known that surface integrity of these materials may be affected by EDM, degrading their tribomechanical characteristics. This work focuses on assessing the use of two different surface modification routes: thermo-mechanical treatments (shot blasting, polishing and final high temperature annealing) and/or physical vapor deposition of hard coatings, for improving the fracture and fatigue strength of an EDM-shaped fine-grained hardmetal grade. In doing so, an optimal EDM's surface finish variant and a diamond ground and polished one are used. Mechanical behavior is evaluated under four-point bending and fatigue characterization is given in terms of fatigue limit following the staircase method. Experimental results indicate that both approaches markedly decrease the lessening effect of EDM on the mechanical strength of hardmetals, although a complete fracture and fatigue strength retention is only achieved by combining both of them. The improved mechanical behavior is rationalized on the basis of the beneficial changes induced by surface modification on the effective residual stress field at the surface of EDM-shaped hardmetals, as assessed by a linear elastic fracture mechanics analysis combined with fractographic examination.

1. Introduction

Hardmetals (WC-Co cemented carbides) are, from a technical viewpoint, one of the most successful cases of "tailor-made" composite materials [1]. The main reason behind it is the feasibility of combining the advantageous properties, without retaining the negative ones, of their two quite different constituents: hard micrometer-sized tungsten carbides embedded in a tough cobalt-rich binder. As a result, hardmetals exhibit a unique combination of hardness, wear resistance and fracture toughness that have positioned them as well-established materials for use not only as tools in the manufacturing industry but also as wear-resistant and structural components in a variety of other industrial sectors. On the other hand, in many of these applications high dimensional accuracy together with complex geometries is frequently required. Thus, the referred elevated hardness, and even more important, the associated brittleness that cemented carbides possess results in technical difficulties and high cost for ensuring close tolerances and surface finish under traditional (diamond-based) machining techniques. To diminish these serious shortcomings, alternative shaping routes are increasingly emerging; and among them, electrical discharge machining (EDM) is the most commonly used for hardmetals [2–4].

The capability of EDM for machining cemented carbides has been proven in terms of performance indexes such as material removal rate or surface roughness (e.g. Refs. [2–8]). However, even for the cases where optimum surface conditions are achieved, EDM of hardmetals usually induces microcracks and unfavorable residual stresses within a thermally affected zone beneath the shaped surface [4–12]. From the perspective of performance, it is clear that the nature and severity of this damage will dictate the mechanical properties of the EDM-shaped hardmetal piece.

The influence of EDM on the fracture and fatigue resistance of WC-Co cemented carbides has been investigated and documented by the authors in recent studies [13,14]. The main findings of these investigations point out a relevant strength degradation of EDM-shaped hardmetals, under both monotonic and cyclic loading, dependent upon the correlation between sizes of processing defects and EDM-induced flaws as well as the level of the tensile residual stresses developed at the shaped surface. This is also in agreement with the inverse relationship between bending strength decreasing and fracture toughness of WC-based cermets reported by Lauwers and coworkers [4]. In this regard, although the development of advanced pulse-type generators and the implementation of multi-step sequential EDM have resulted in clear surface integrity improvements [11,13–16], it is evident that additional post-EDM actions are

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mandatory, if the mechanical strength of EDM-treated cemented carbides is to be enhanced.

Post-EDM surface treatments either by mechanical means (ultrasonic machining and abrasive blasting on ceramic composites [17–19]) or material surface deposition (coatings on hardmetals [20]) have been shown to be effective routes for improving the EDM-induced fracture strength degradation. The coating approach has also been reported as beneficial for improving the fatigue life of an EDMed D2 tool steel [21]. Furthermore, and in this case of special application to cemented carbides, it is well known that residual surface stresses (either induced by conventional abrasive grinding or associated with mechanical precracking procedures) may be released through high-temperature annealing [22,23]. In this work, all these treatments are implemented, either as individual options or as a combined one, for enhancing the fatigue performance of an EDM-shaped fine-grained hardmetal. Fatigue limit and fatigue sensitivity (the ratio between fatigue limit and flexural strength) are used as discriminative parameters to assess the effectiveness of the post-EDM options.

2. Experimental procedure

The material studied was a commercial fine-grained WC-10%wt. Co hardmetal grade (HV30 = 15.4 GPa) produced by DURIT Metalurgia Portuguesa do Tungsténio. It was supplied as rectangular bars of 4 × 3 × 45 mm dimensions. The investigation focused on an optimal EDM surface condition, here simply referred to as *EDM*, as compared to a reference ground and polished one, in this study designated as *P*. The former was accomplished by a sequential 10-step EDM using a wire-machine with an advanced pulse-type power supply (Model ROBOFIL 2020SI, Charmilles Technologies). Surface integrity optimization was attained by limiting the maximum cutting rate to values below 2 mm/min during the surface finish sequences (last seven steps). Surface integrity features for both conditions have been reported in detail elsewhere [11], and may be summarized in terms of: (1) presence of 5–10 μm in-depth microcracks at the EDM-shaped surface; and (2) average roughness value several times higher for the *EDM* variant (between 0.05 and 0.10 μm) as compared to that determined for the *P* one (0.01 μm).

Regarding post-EDM treatments, three different procedures were pursued for increasing the mechanical strength determined for the *EDM* condition: (1) a two-step thermomechanical treatment route, (2) thin film deposition, and (3) a combination of the previous two routes. The first one consisted of shot-blasting of the machined surface using small glass spheres, followed by diamond polishing, and finally thermal annealing in vacuum at 920 °C for 1 h. The attained condition, referred to as *EDM + TT*, exhibited surface roughness parameters similar to those measured on the reference *P*. For the second route, a titanium nitride (TiN) film was deposited on the substrates machined by EDM, following Balzers's physical vapor deposition (PVD) — arc ion plating process, yielding a surface condition named *EDM + TiN*. For comparison purposes, similar surface treatment was conducted on a specimen with surface finish *P*, resulting in the *P + TiN* variant. Extensive microstructural and mechanical characterization, including residual stress assessment, adhesion strength and microabrasive wear resistance have been reported elsewhere [20,24,25] for both *EDM + TiN* and *P + TiN* surface conditions. The coatings were dense and uniform (3 μm in thickness). The stress analyses performed, using X-ray diffraction $\sin^2\psi$ method, indicated large residual compressive stresses (of about 2 GPa) within the film, independent of the substrate surface condition [20]. Additionally, adhesion strength assessed by means of both indentation and scratch tests yielded high (and similar) values for indentation adhesion parameters (i.e. critical normal load for lateral crack generation and interfacial fracture toughness) and scratch resistance (i.e. critical normal load for adhesive failure under unidirectional sliding contact) of both surface conditions [24,25]. This was also the case for the tribomechanical response evaluated by means of crater grinder tests, as given by alike intrinsic wear coefficients for the TiN layers deposited on *EDM* and *P* substrates [25]. Finally, the third route was a sequential combination of procedures (1) and (2), and the resulting condition is designated as *EDM + TT + TiN*.

In all the cases, both fracture and fatigue behavior were evaluated in four-point bending using a standard 20 × 40 mm fully articulating fixture. Flexural strength was measured using a servohydraulic testing machine (model 8511, Instron Ltd.) at an applied loading rate of 200 N/s. At least ten specimens were tested for each surface condition. Regarding cyclic loading, testing was aimed to determine fatigue limit, defined as the fatigue strength corresponding to an "infinite" life of 2×10^6 cycles. It was done following the staircase or up-and-down method [26] using a large number of specimens. Fatigue experiments were carried out employing a resonant testing machine (model MIKROTRON, RUMUL) at working frequencies of about 170 Hz and a load ratio $[R = (\sigma_{min}/\sigma_{max})]$ of 0.1.

Fracture surfaces for selected broken specimens were inspected using scanning electron microscopy — SEM (Model JMS-6400, Jeol Ltd.). For each sample examined, possible fracture initiation sites were first traced back, at low magnification, from sequential sets of fracture markings. Particular areas of interest were then observed at higher magnification in order to identify and document strength-limiting flaws. Fractographically derived flaw information included the nature, location, shape geometry, and size (commonly the depth). The experimental data was then used for evaluating comparisons between observed and estimated flaw sizes, the latter calculated from the fundamental linear elastic fracture mechanics (LEFM) correlation among critical defect size, strength and fracture toughness. Inconsistent results were taken as an indicator of residual stress effects.

3. Results and discussion

3.1. EDM-induced strength degradation

Mean and standard deviation values for the flexural strength (σ_r) of the surface variants investigated are given in Table 1. It is clear that average σ_r value for the *EDM* surface variant is considerably lower (more than half) than the one determined for the *P* surface variant. After mechanical testing, the fractographic analysis of broken specimens indicated fracture origins of similar size (Fig. 1 and Table 1) but different nature and location, depending on the surface condition under consideration. For the *EDM* specimens EDM-induced surface flaws were identified as critical defects, whereas processing heterogeneities contained within the bulk were discerned to play such a role for those with surface condition *P* (Fig. 1). As will be discussed later, the latter also applies for the *P + TiN* specimens. In order to rationalize the experimental findings, fracture results were analyzed on the basis of LEFM by comparing estimated and observed critical flaw size (a_c), the latter as experimentally determined from SEM

Table 1
Flexural strength, critical flaw size and estimated surface residual stresses for the different surface conditions investigated.

Surface condition	Flexural strength, σ_r [MPa]	Critical flaw size, a_c		Estimated residual stress at the surface, σ_{res} [GPa]
		Experimental [μm]	Estimated [μm]	
EDM	1337 ± 25	4–13	25	0.7–2.8
EDM + TT	2284 ± 331	4–11	8	0.1–1.0
EDM + TiN	1942 ± 163	8–9	15	0.6–0.7
EDM + TT + TiN	2529 ± 241	9–10	9	0.0–0.3
P	2869 ± 234	7–9	8	–
P + TiN	2841 ± 296	5–8	8	–