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Reprint of "Thermal fatigue behaviour of WC-20Co and WC-30(CoNiCrFe) cemented carbide"☆

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A B S T R A C T

Cemented carbides are used in many applications, such as drawing dies, cutting tools and hot rolls. In applications where cyclic temperature variations are present, an important factor that must be taken into account is thermal fatigue (TF). In this study, TF behaviour of two commercial cemented carbides was evaluated by means of a custom test configuration inducing a biaxial state of stress. At an early stage of the damage process, crack density is higher in WC-30(CoNiCrFe), while crack length is lower than WC-20Co. At a later stage cracking proceeds by propagation of existing cracks, partly reducing the difference between the two grades. The prevailing fracture modes are different in the two materials. In WC-20Co the main fractures occur at the WC/WC grain boundary and at WC/Co interface. In WC-30(CoNiCrFe) cracking proceeds by fracture of carbide particles and shear fracture of binder phase. A possible influence of oxidation on the TF crack propagation has been evidenced.

1. Introduction

Cemented carbides are composite materials formed by high fraction of hard WC particles bonded by a soft and ductile Co binder. They possess a high hardness and excellent wear resistance. Mechanical properties are strongly related to microstructure, namely to the binder content and carbide grain size. An increase in binder content and in WC grain size leads to a decrease of hardness, and to an increase in the fracture toughness [1,2], while transversal rupture strength rises up to a maximum and then diminishes [3]. The properties may be therefore tailored to the specific applications by changing the microstructure parameters.

Cemented carbide components undergo Thermal Fatigue (TF) damage in applications involving rapid temperature variations that lead to strong thermal gradients. An example is milling where thermo-mechanical cyclic loads lead to the formation of comb cracks perpendicular to the cutting edge in the hardmetal tool [4]. This damage was widely characterized by J. Garcia et al. [5]. TF is a typical oligo-cyclic fatigue phenomenon [6], which promotes the initiation of a fine crack network (heat cracking) on the surface with small penetration depth. In most cases, heat cracking leads to the deterioration of the tool surface finishing, which generally impairs the surface condition of the worked material. TF alone may cause catastrophic failure rarely, while the occurrence of a secondary damage phenomenon (e.g. wear, contact fatigue…) enhances crack propagation, thus promoting a premature loss of structural integrity. The selection of a most appropriate material or/and the development of best operational practices can either prevent or delay the TF damage.

In an empirical approach based on the theory of thermo-elasticity and fracture mechanics, it is possible to correlate the thermal shock (TS) resistance of cemented carbides to the parameter $kTRS/E\alpha$, where k is the thermal conductivity, TRS is the transverse rupture strength, E is Young's modulus and α is the coefficient of thermal expansion [1,7]. This parameter is often used to predict the TF resistance, as well. A few authors studied the TF resistance of cemented carbides. When cemented carbides are subject to repeated TS, Tumanov et al. [8] found that microstresses are accumulated in the material because of the different thermal expansion coefficients of WC and Co. A reduction in the Co content leads to a reduction in the TS resistance because of the increase in tensile stresses in the metal matrix. Lagerquist [9] investigated the TF of cemented carbide hot roll and concluded that an increase in the cobalt content and in the WC grain size leads to an increased number of cracks but to a decreased propagation rate. However the influence of grain size becomes fundamental only in case of low amount of cobalt. The common fracture modes that can occur in the cemented carbides are cleavage of WC particles, fracture at the WC/WC grain boundary and at the WC/Co interface, and shear fracture of binder phase. The ratio of transgranular/intergranular fracture of WC increases with the WC grain size [3]. Cracks nucleate at the surface and propagate preferentially at the WC/WC grain boundary and the WC/Co interface. Ning et al. stated that thermal cracking proceeds by nucleation, growth and aggregation of microvoids at the interface between WC/Co [10]. The overall damage was found to be proportional to the maximum temperature during thermal cycling and a higher cooling rate favoured more pronounced cracking. Ishihara

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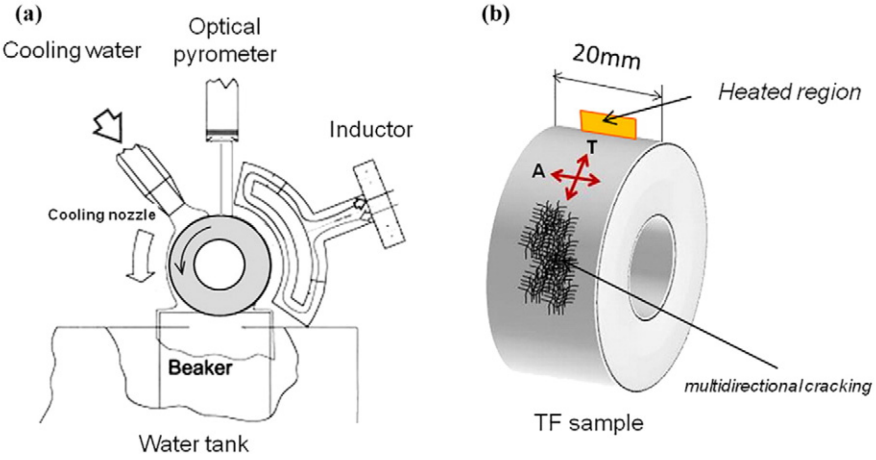

Fig. 1. Customary rig used for TF fatigue cracking (a). TF sample showing multiaxial stress state (T = tangential, A = axial) and multidirectional thermal cracking (b).

confirmed a similar mechanism for 72WC-8TiC-8TaC-2NbC-10Co and stated that cracks mostly propagate through the metal binder or at the interface with the WC phase, following a zigzag path [11].

Another important parameter in applications characterized by rapid temperature variations is the oxidation resistance. Most of the data regarding oxidation resistance of WC-Co alloys are related to a temperature range between 500 and 1000 °C in different atmospheres (air, Ar/O_2 mixture or O_2) [12–17]. In all cases, WO_3, $CoWO_4$ and Co oxides were observed. An increase in the binder content leads to an improved oxidation behaviour because of a higher amount of $CoWO_4$ that is denser and more protective than the WO_3. After L. Chen et al. [18] the oxidation of cobalt occurs due before that of WC, due to its faster oxidation kinetics. Voitovich et al. [16] also studied the effect of partial and complete substitution of Co by Ni. In the temperature range between 500 and 800 °C the oxidation of Co is faster than that of Ni. Ni reduces the oxidation resistance since WO_3 becomes the main oxidation product. Aristizabal et al. [19–21] confirm that the oxidation resistance increases with the binder content but decreases on increasing the Ni/Co ratio. Nevertheless, the negative effect of Ni is negligible in case of 15 wt.% binder and becomes important at 25 wt.% binder.

Few data are available in literature on the TF resistance of cemented carbides with high Co content. The aim of the present study was to evaluate the TF resistance of two commercial cemented carbides by means of a custom test configuration that induce a biaxial state of stress in a harsh oxidizing environment.

2. Materials and methods

Two different commercial cemented carbide grades containing 20 wt.%Co (WC-20Co) and 19 wt.%Co-9.5 wt.%Ni-1 wt.%Cr-0.5 wt.%Fe (WC-30CoNiCrFe) were selected for present investigation. A complete microstructural characterization was carried out after proper metallographic preparation. Murakami's reagent (100 ml distilled water, 5–10 g KOH or NaOH, 5–10 g $K_3[Fe(CN)_6]$) [22], was used for selective etching of WC particles. The composition of the two materials was investigated by EDXS. Mean grain size (D_{WC}), contiguity (C) and mean binder free path (λ) were determined on SEM micrographs at 3000×. Contiguity measures the carbide contacts and the mean binder free path is the average thickness of cobalt between the WC particles. These parameters are defined by Eqs. (1), (2) and (3) [23,24].

$$D_{WC} = \sum_i^n l_i^{\,4} / \sum_i^n l_i^{\,3} \tag{1}$$

$$C = 2 \times (N_L)_{WC-WC} / \left(2 \times (N_L)_{WC-WC+} (N_L)_{WC-Co}\right) \tag{2}$$

$$\lambda = 2 \times f_{V\_Co} / (N_L)_{WC-Co} \tag{3}$$

where

l_i	measured intercept length;
f_{V_Co}	Co volumetric fraction;
n	numbers of WC grains intercepted;

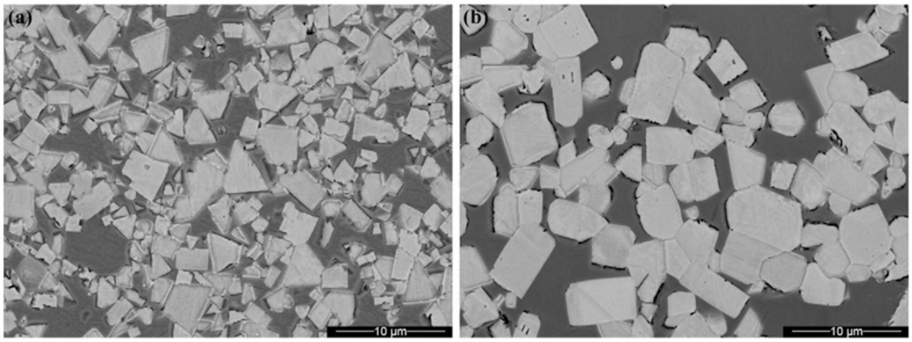

Fig. 2. WC-20Co (a) and WC-30(CoNiCrFe) (b) SEM micrographs.