Residual strength of WC-Co cemented carbides after being subjected to abrupt temperature changes

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Abstract

Thermal shock and thermal fatigue are recognized as common failure modes for WC-Co cemented carbides (hardmetals) in several applications involving service temperature changes. However, information on microstructure-performance for these materials when subjected to abrupt changes in temperature is rather limited. In this investigation, the thermal shock resistance of two WC-Co cemented carbides is studied on the basis of their residual strength after being subjected to temperature changes. The materials studied correspond to grades with different grain size (medium and ultrafine) but similar binder content. Thermal shock variables include two temperature difference ranges (400ºC and 550ºC) as well as number of abrupt changes (1, 3 and 10). Residual strength results were related to parameters extracted from Hasselman's theory. It is found that medium-sized hardmetal exhibits a higher strength loss in the first quenching cycle but a greater damage tolerance to repeated thermal shocks than the ultrafine-sized. The assessed residual strength trends are in agreement with those expected from evaluation of Hasselman's parameters for quantifying resistance to either crack initiation or crack propagation induced by thermal shock.

Keywords: Cemented carbides, Residual strength, Thermal shock, Hasselman's parameters

1 Introduction

WC-Co cemented carbides, also called hardmetals, combine the hardness and wear resistance of the ceramic phase (normally WC) with the toughness of the metallic one (usually cobalt)[1]. Due to its outstanding properties, hardmetals are the best option in a wide range of applications that are exposed to harsh service conditions such as corrosive environments, high temperatures or abrupt temperature changes. On the other hand, despite its exceptional thermal conductivity and excellent fracture toughness in comparison with ceramic materials, cemented carbides are sensitive to thermal shock due to its brittle-like nature behavior [2]. Thus, thermal cracking and thermal fatigue (e.g. Refs. [3-5]) are recognized as common modes of failure in different applications where hardmetals are involved (e.g. intermittent cutting [4,6] and rock drilling [7]).However, different to the case where pure mechanical loads are implied, studies devoted to thermal shock resistance of hardmetals are relatively scarce (e.g. Refs. [8-12]). Within this context, it is the purpose of the present research to assess the influence of carbide grain size on the strength degradation of two WC-Co cemented carbides after being subjected to abrupt temperature changes. In doing so, following the approach proposed by Mai [8], experimental data is analyzed and discussed on the basis of Hasselman's parameters [13,14] for assessment of thermal shock resistance in structural materials.

2 Materials & Methods

The investigated materials are two hardmetal grades with different carbide grain size, one ultrafine and another medium-grained, and similar binder content. They correspond to experimental grades supplied by Sandvik Hyperion. Key microstructural parameters, including binder content ($\%_{wt.}$), mean grain size (d_{WC}), carbide contiguity (C_{WC}), and binder mean free path (λ_{binder}) are listed in **Table 1**.

Table 1: Microstructural parameters for the studied materials**.**

Specimen code	Wt.% binder	d_{WC} (μm)	C_{WC}	λ_{binder} (μm)
10CoUF	10	0.4 ± 0.2	0.46 ± 0.06	0.16 ± 0.06
11CoM	11	1.1 ± 0.7	0.38 ± 0.11	0.42 ± 0.29

As mentioned above, one of the purposes of this investigation is to correlate the strength loss in cemented carbide due to thermal shock with Hasselman's parameters. Thus, for the determination of these thermal shock parameters several material properties were measured or estimated from equations proposed in literature. They include: Poisson ratio (υ), flexural strength (σ_f), fracture toughness (K_{Ic}), elastic modulus (E) and coefficient of thermal expansion (CTE).Poisson ratio and CTE were determined by applying the rule of mixtures for composite materials [15]. Flexural strength was measured by four-point bending, using a fully articulated test jig with inner and outer spans of 20 and 40 mm, respectively. These tests were performed on an Instron 8511 servohydraulic machine at a load rate of 100N/s and at least 15 specimens of 45x4x3 mm dimensions were tested per grade. The surface which was later subjected to the maximum tensile loads was polished to mirror-like finish and the edges were chamfered to reduce their effect as stress raisers. This sample preparation and strength testing procedures were also followed for assessment of mechanical integrity of specimens subjected to abrupt temperature changes. Fracture toughness was measured by testing to rupture a single edge pre-cracked specimen, following the procedure described by Torres et al. [16]. Finally, the elastic modulus was determined by means of the "Impulse excitation of vibration" method, according to the ASTM E-1876 standard [17].

Thermal shock was induced on the above samples by: (1) heating up in a Hobersal 12 PR/300 furnace at a heating rate of 10ºC/min, (2) holding at the maximum temperature for 15 minutes, and (3) final water quenching. Two different abrupt temperature changes, 400ºC and 550ºC, and three different number of quenching cycles - N_c = 1, 3 and 10 - were selected. Changes induced by thermal shock were assessed by measuring the retained flexural strength at room temperature. At least 3 specimens were tested per temperature difference and number of thermal shock cycles. After failure, a detailed fractographic inspection was carried out in order to identify critical flaws using a JEOL-7001F field emission scanning electron microscope. After thermal shock the elastic modulus was also determined in order to discern possible microcracking of the specimens.

3 Results and discussions

Retained strength after abrupt temperature change against the number of thermal shock cycles is shown in **Fig. 1** for the two investigated temperature differences. In **Fig. 2** same experimental data is plotted as normalized strength loss, using as reference baseline the strength exhibited by specimens just ground and polished. From these graphs, it is clear that (1) cemented carbides are sensitive to thermal shock and (2) both temperature difference and number of thermal shock cycles, have an important influence on the determined strength degradation. Regarding microstructural effects, it is observed that 10CoUF grade do not show a significant strength drop at the 1st thermal shock cycle for both studied temperature differences. Contrarily, a strength loss of about 15% is evidenced for 11CoM grade when subjected to ΔT of 550ºC. However, as the number of quenching cycles increases, the trend is reversed and strength lessening is less pronounced for the medium-grained grade than for the ultrafine one. Thus, it may be concluded that the investigated ultrafine grade exhibits a higher thermal shock resistance for a unique quenching cycle than the medium grain-sized cemented carbide, but the former is more sensitive (in terms of strength degradation) to repeated thermal shocks than the latter.

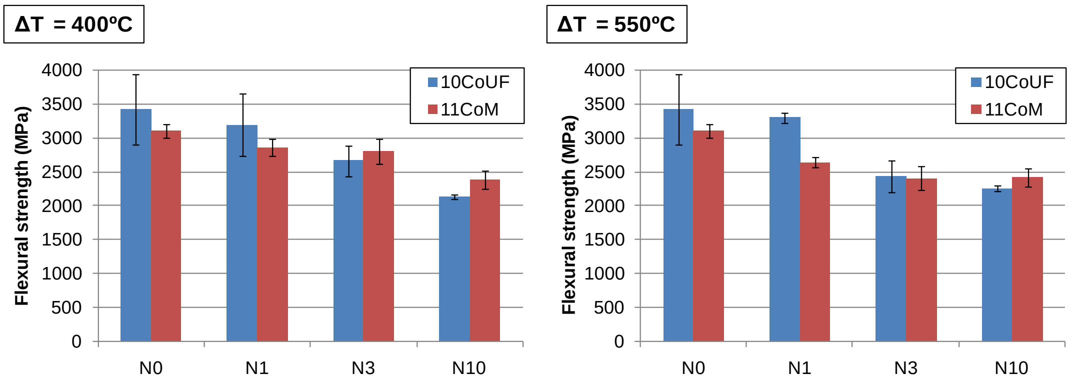

Fig. 1: Flexural strength as a function of the number of quenching cycles at two different abrupt temperature changes - 400ºC (left) and 550ºC (right) -for the investigated hardmetals.

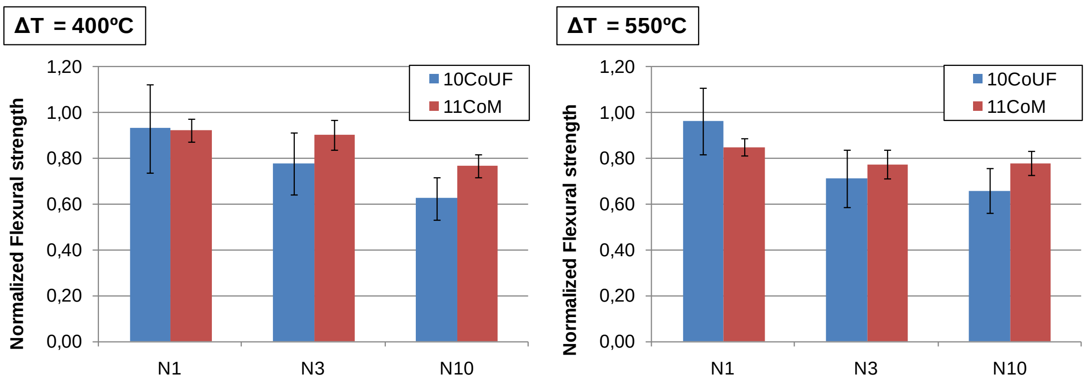

Fig. 2: Normalized flexural strength as a function of the number of quenching cycles at two different abrupt temperature changes - 400ºC (left) and 550ºC (right) - for the investigated hardmetals.

A detailed fractographic inspection of the broken samples was conducted, in order to identify flaws that act as initiation sites for failure as well as to discern possible thermal shock damage. It was found that thermal shock cycles do not imply changes in the nature of failure controlling flaws. However, in some cases, evidence of local microcracking in the vicinity of these critical defects was discerned (e.g. **Fig.3**).Hence, subcritical growth of preexisting defects (and thus, variations in their size and geometry) could be speculated to occur as a result of the abrupt temperature changes induced in the materials studied. Aiming to evaluate whether referred microcracking (damage) was either general or localized, elastic modulus of specimens subjected to thermal shocks was measured. No changes were determined in the stiffness of specimens after thermal shocks, suggesting that microcracking was rather a localized phenomenon. Thus, evidenced strength loss after thermal shock may be related to subcritical growth (directly related to microcracking) in the vicinity of the intrinsic flaws of the material.

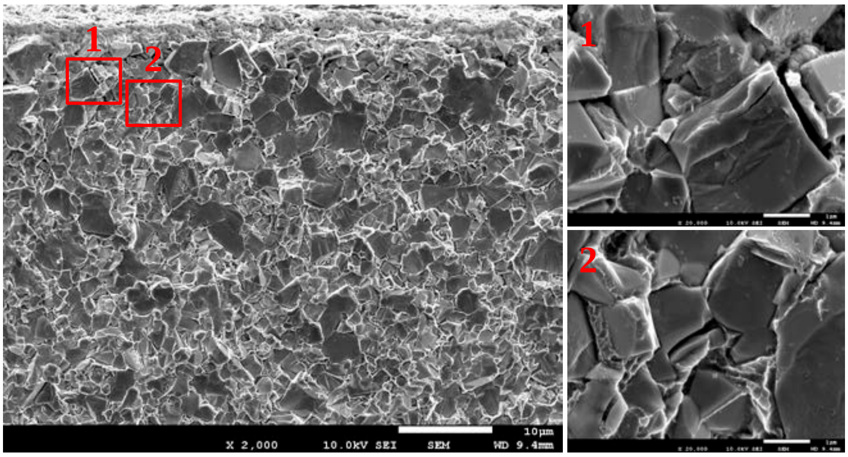

Fig. 3: Coarse-carbide agglomerate acting as failure initiation site for the investigated 11CoM grade after 10 quenching cycles for an abrupt temperature change of 550ºC. Microcracking in the vicinity of the flaw is evidenced.

Hasselman's theory is frequently invoked to rationalize the strength degradation of ceramic materials due to thermal shock. In this investigation, Hasselman's parameters R and R'''' were determined for the studied hardmetals, and a correlation between them and the attained strength degradation results was attempted. First Hasselman's parameter (R) can be estimated [13,14] according to:

$$R = \frac{\sigma_f(1-\nu)}{E\alpha} \qquad (1)$$

R is measured on ºC, and refers to the critical quenching temperature to induce fracture in the material. For damage resistance or extent of crack propagation, the Hasselman's resistance parameter (R'''') must be introduced [13,14]. This parameter is given as follows:

$$R'''' = \frac{1}{2(1-\nu)}\left(\frac{K_{Ic}}{\sigma_f}\right)^2 \qquad (2)$$

Measured Hasselman's parameters for the studied cemented carbides are shown in **Table 2**, together with elastic modulus, flexural strength, fracture toughness, Poisson ratio and CTE values. According to Hasselman's parameters, 11CoM grade should be expected (1) to experience crack initiation at lower temperature differences, and (2) to exhibit higher damage tolerance to crack propagation than 10CoUF hardmetal. The trends indicated by the Hasselman's parameters are in satisfactory agreement with those determined from the experimental results, on the basis of strength retention after single or repetitive thermal shocks.

Table 2: Elastic modulus, flexural strength, fracture toughness, Poisson ratio, coefficient of thermal expansion and R and R'''' Hasselman's parameters for the investigated materials.

Specimen code	E (GPa)	σ_f (MPa)	K_{Ic} (MPa)	υ	α (K^{-1})	R (ºC)	R'''' (µm)
10CoUF	577	3422	10.3	0.24	6.62E-06	682	5.9
11CoM	582	3101	13.9	0.24	6.75E-06	600	13.2

4 Conclusions

In this study, the residual strength of two WC-Co cemented carbides after being subjected to abrupt temperature changes has been investigated. From the attained results the following conclusions may be drawn:

1. Cemented carbides are sensitive to abrupt changes of temperature. Both studied materials exhibit an important strength loss when subjected to thermal shock. For the studied temperature ranges, results indicate that the number of thermal shock cycles have a major influence than the quenching temperature difference on the strength degradation of the studied hardmetals.

2. Within the range of experimental variables investigated, the main change induced by thermal shock is speculated to be subcritical growth of the intrinsic flaws, as related to localized microcracking. Thus, as the number of thermal shock repeats increases, the effective size of potential critical defects becomes larger and corresponding flexural strength is increasingly lessened.

3. The studied grade with finer grain size exhibits a higher resistance to damage initiation (induced by thermal shock) than the medium-grained one. On the other hand, the former is found to be more sensitive to the propagation of this damage than the latter. Such microstructural trends are in satisfactory agreement with those expected from the relative difference for Hasselman's parameters for both materials.

Acknowledgements

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