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HIGH TEMPERATURE MECHANICAL BEHAVIOUR OF CEMENTED CARBIDES

WC - (6.5, 12, 15 AND 25) % Co

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Résumé - Le module élastique et la contrainte à la rupture sont déterminés pour quatre nuances : WC- (6,5 - 12 - 15 et 25) % Co jusqu'à 1000°C. La variation du module de WEIBULL est mesurée en température pour la nuance WC-6,5 % Co. Les mesures de ténacité sont réalisées jusqu'à 800°C sur trois nuances : WC - (6,5 - 15 et 25)% Co et la validité de ces mesures est discutée en utilisant les critères de rupture classique.

Abstract - Elastic modulus and fracture strength have been determined up to 1000°C in the case of WC-Co materials with different composition (6.5 - 12 - 15 and 25) % wt Co. Temperature dependence of WEIBULL modulus has been observed for WC - 6.5 % wt Co composition. Fracture toughness has been characterized up to 800°C for WC - (6.5 - 15 and 25)% wt Co and the validity of these results is discussed according to fracture mechanics criteria.

I - INTRODUCTION

Cemented carbides are widely used materials for industrial applications in metal cutting and rock drilling. These composites materials, made of hard tungsten carbide and softer cobalt binder phase, combine high hardness, strength and toughness as well as wear resistance. Most of studies devoted to these materials focused on room temperature behaviour /1/. Several attempts have been made to explain the room temperature fracture behaviour and different theoretical models have been advanced. Only a few papers deal with temperature behaviour /2, 3, 4/ and so there is a lack of knowledge about deformation mechanisms at high temperature and specially above 600°C. In usual applications, high stresses and high temperatures are generated locally at the tool surface and temperatures up to 1000°C have been recorded in metal cutting operations /5/. In the present work, the fracture strength, toughness and elastic modulus of three industrial WC-Co grades are determined up to 1000°C. Results are discussed on the basis of microstructure.

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II- EXPERIMENTAL PROCEDURE

II-1- Materials

Studied materials are industrial grades (*) with different contents of cobalt phase. The mean size of WC grains is about 2.5 μm . All specimens have been made by pressureless sintering between (1340-1440) $^{\circ}\text{C}$ in hydrogen. Main characteristics are listed in table 1.

Grade	G1	G2	G3	G5
% Co(wt)	6.5	12	15	25
Density	14.9	14.1	14.03	13.1

Table 1 : Main characteristics of studied materials.

In case of low Co content, the contiguity between carbide grains is important and the cobalt phase is present in some places as thin films. Residual porosity has been observed for each grade (A, B and sometimes C type (ASTM recommendation)).

II-2- Experiment

Mechanical properties have been measured by four point bending tests (with a span dimension 24 / 8 mm) under controlled atmosphere (95 % N_2 + 5 % H_2) with a high temperature apparatus /6/. All tests were performed at a crosshead speed of 0.1 mm/min. Fracture strength (σ_f) and elastic modulus (E) measurements were carried out with carefully polished specimens (2x4x30 mm³) up to 1000 $^{\circ}\text{C}$. For fracture toughness (K_{IC}) values determination, a "V" notch was introduced with a low speed diamond saw on 4x6x30 mm³ specimens (S.E.N.B. type) ; the pre-notch was extended to a very sharp notch by spark erosion using a 25 μm width tungsten foil. To verify the K_{IC} validity measurements, we have applied the mechanical fracture criterion. Results show that Linear Elastic Fracture Mechanics theory cannot be applied above 800 $^{\circ}\text{C}$ for G1 composition and above 600 $^{\circ}\text{C}$ for G3 and G5. So we have used the J integral fracture criterion with compliance method /7/. In order to characterize the fracture toughness of G3 grade up to 1000 $^{\circ}\text{C}$ we have determined the critical parameter " J_{IC} " which leads to a significant " K_{IC} " value

III - RESULTS

At room temperature, there is a decrease of elastic modulus with an increase of fracture strength as the cobalt content increases (from 6.5 % to 25 %). Cemented carbides room temperature fracture mode is mainly of brittle type. Thus the mechanical behaviour can be explained in terms of Griffith's theory : for a given grade, the strength is determined by the fracture energy and the size of critical defects. Weibull statistical analysis has been applied to obtain a quantitative estimation of observed strength dispersion : G1, G3 and G5 grades exhibit similar Weibull modulus (m) between 5 and 8. This modulus is quite low, but same values have reported for similar sintered cemented carbides ; higher modulus needs specific sintering processes as HIP /8/. In case of G1 grade, Weibull modulus temperature dependence has been observed: m is nearly constant up to 600 $^{\circ}\text{C}$ and is slightly increased at higher temperatures . The decrease of elastic modulus (E) and fracture strength (σ_f) values (see fig.1,2) is observed from (300-400) $^{\circ}\text{C}$ for all grades /9/. While for the low Co content grade (G1) fracture strength is lower than the values for the other grades, the decrease with temperature is not so large for G1 (up to 600 $^{\circ}\text{C}$). This can be correlated to the absence of major plasticity in G1 grade at low and medium temperatures.

At room temperature, the fracture toughness (K_{IC}) increases with the cobalt content ; this point has been observed by different authors /10/. Fracture energy (e.g. critical strain energy release rate : G_{IC}) is obtained from E and K_{IC} experimental values.

Figure 1: σ_f versus temperature of WC-Co grades.

Figure 2: E versus temperature of WC-Co grades.

On figure 3, we have reported the G_{IC} temperature dependence : we observe nearly constant values up to 300°C, a maximum at 400°C, and a gradual increase at higher temperatures.

Figure 3: G_{IC} versus temperature for G1, G3, and G5.

IV - DISCUSSION

Room temperature strength is controlled by processing defects : predominant defects in all studied grades are large pores of A type ($>10 \mu m$), B type ($>40 \mu m$) and sometimes C type (Eta phase " η "). This has been confirmed by S.E.M. observations of fracture origins [9] and is consistent with flaw sizes (a_c). The equivalent critical flaw size is calculated from strength and toughness experimental values :

$$a_c = \frac{1}{1.21 \pi} \left(\frac{K_{IC}}{\sigma_F} \right)^2 \quad [9/]$$

Fracture mode is intergranular for smaller grains and transgranular in case of larger carbide grains. There is a slight increase of a_c with temperature : this can be explained by subcritical crack growth mechanisms with coalescence or linking of pre-existing smaller defects. Microcracks network can effectively be observed on high temperature fracture faces.

(G1 grade)	25°C	600°C	700°C	800°C
a_c (μm)	10	25	30	60
Weibull modulus m	5	6	-	8

Table 2 : Critical flaw sizes and Weibull modulus at different temperatures

According to figure 3, the high temperature behaviour of cemented carbides can be divided into three temperature fields :

i) Between room temperature and 300°C (zone I) : G_{IC} is nearly constant, and fracture is of brittle type for small cobalt content grade. In case of cobalt

content higher than 15 %, cemented carbides exhibit macroscopic plasticity (G3 and G5 grades).

However, we don't observe any difference in the fracture initiation defects for each grade ; that means processing defects (pores) control the low temperature mechanical behaviour of all studied materials.

ii) Between 300 and 800°C (zone II) : the ductility of cobalt phase increases. The fracture energy G_{IC} is increased by reduction of crack tip stress field in the plastic zone by energy dissipation through plastic relaxation occurring in the soft phase (cobalt phase). This phenomenon is accentuated for higher Co contents. In this temperature zone, all grades present important plastic deformation by grain boundary sliding (in the cobalt phase) leading to the observed decrease of elastic modulus and fracture strength.

A first maximum of " G_{IC} " is observed for all grades at about 400°C. This behaviour can be interpreted in terms of toughening effects of the cobalt phase produced by different phenomena such as the change in magnetic anisotropy (HCP Co), the allotropic transformation (HCP to FCC), the hardening of Co phase by precipitation or formation of secondary phases /11, 12/. This point has to be confirmed and different experiments are now running to identify the effective toughening mechanism. High temperature X.R. analysis have been performed recently (in H_2) with our specimens; first results show significant formation of secondary compounds as Co_3W . The amplitude of this low temperature G_{IC} maximum is increased with cobalt volumic fraction. Until now this phenomenon has never been observed (to our knowledge) in cemented carbides. Extensive experiments have to be performed to confirm this toughening effect.

iii) At higher temperatures (>800°C) zone III : All the properties show a drastic decrease probably due to the low yield strength of the cobalt above 800°C and the materials have a tendency to exhibit creep deformations. The Linear Elastic Fracture Mechanics criteria are not valid /9/.

V-CONCLUSION

Fracture toughness (or critical strain energy release rate G_{IC}) temperature dependence, define different fracture modes :

- . Zone I (20-300°C) : brittle fracture mode, with strength controlled by processing defects.
- . Zone II (300-800°C) : increase of fracture energy by plastic relaxation in the cobalt phase with an important decrease of fracture strength. An apparent toughening effect has been observed at 400°C.
- . Zone III (>800°C) : all properties decrease.

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