FRACTURE STRENGTH OF WC-Co ALLOYS①

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ABSTRACT Considering the classic Griffith-Orowan equation of energy balance during fracture and the contribution of the tungsten carbide and the effective cobalt phase volume fraction to the fracture strength, a new theory, which concerns the variations of the fracture strength of WC-Co alloys with their microstructural parameters such as the cobalt phase volume fraction and tungsten carbide grain size, was proposed. The predications provided by this theory tally qualitatively well with the experimental results observed by the previous researchers.

Key words fracture strength cobalt phase volume fraction WC grain size

1 INTRODUCTION

Cemented carbides have found their applications in many industrial fields because of their high strength and excellent resistances to chemical corrosion and mechanical wear since they came out in 1920's. Many attempts[1, 2, 3, 6, 7] were made to explain the relation of fracture strength σ_{bb} of the WC-Co alloys *vs* the content of cobalt phase. However, none of them could give a perfect explanation, and so-called right branch or left branch theories on the fracture strength were developed for different composition ranges of WC-Co alloys. In fact, for practical WC-Co alloys, an identical fracture model should be followed although the fracture mechanism possibly changes locally. In addition, the application of dispersion-strengthening theory for the dispersion-strengthened alloys to the study of the fracture of practical WC-Co alloys is questioned because of the particle size and its volume fraction requirements.

In the present paper, the author proposed a new model based on the Griffith-Orowan equation in consideration of the contributions of WC particles and effective cobalt volume fraction to the fracture resistances of the alloys. In this theory on the strength of the WC-Co alloys, the strength is related to the microstructural parameters and some physical constants of the related components. The theory is suitable for the description of the strength of cermets and two typical phase materials similar to WC-Co alloys.

2 MODEL

It is well-known that the WC-Co alloys are composed of two fundamental components, *i.e.* WC grain and cobalt phase surrounding the WC grain. When a force is loaded on the WC-Co alloys, the deformation incompatibility appears due to the difference of elastic moduli between the two phases, and a maximum stress will be achieved at the interface between them. If the fracture does not occur at the interface, the assumption that the initial flaw size C in the alloys is proportional to the WC grain size D_{WC}, is plausible. According to this assumption, we have

$$C = bD_{WC} \quad (1)$$

where b is a proportionality dominated by the WC grain shape and composition. Generally, the practical WC-Co alloys may be considered as quasi-brittle solids, and the Griffith-Orowan equation is applicable to describing the fracture of the WC-Co alloys. The expression is given by

$$\sigma_{bb}^2 = 2E(\gamma + P)/(\pi b D_{WC}) \quad (2)$$

where γ and P are the surface energy and the

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plastic deformation work of the cemented carbide, respectively, and their expressions can be described by

$$\gamma = \gamma_{WC}(1-f) + f\gamma_{Co} \qquad (3)$$

$$P = P_{WC}(1-f) + fP_{Co} \qquad (4)$$

where f is the cobalt phase volume fraction. However, since $\gamma_{WC} \gg \gamma_{Co}$ and $(1-f) > f$, $\gamma = (1-f)\gamma_{WC}$; while $P_{Co} \gg P_{WC}$, $P = fP_{Co}$. Therefore, we have

$$\sigma_{bb}^2 = BE[\gamma_{WC}(1-f) + fP_{Co}]/D_{WC} \qquad (5)$$

where $B = 2/(\pi b)$, γ_{WC} is the surface energy of the tungsten carbide, P_{Co} is the plastic deformation work of the cobalt phase. However, the second term fP_{Co} overestimates the contribution of the cobalt phase to the strength of the WC–Co alloys. In fact, the plastic deformation work is partially consumed before the crack propagates through the alloy because of thermal expansion difference between the WC grain and the cobalt in the WC–Co alloys. If the cobalt thickness of the plastic deformation layer around the WC grain is t, independent of D_{WC}, the effective volume fraction of the cobalt phase is given by

$$f_e = f - 2(1-f)t/D_{WC} \qquad (6)$$

and the Young's elastic modulus E of the alloy can be depicted by the mixture rule as

$$E = E_{WC} - (E_{WC} - E_{Co})f \qquad (7)$$

where E_{WC} and E_{Co} are the Young's elastic moduli of the tungsten carbide and the cobalt phase respectively. Combining equation (5) with the expressions of E and f_e obtains

$$\sigma_{bb}^2 = B[E_{WC} - (E_{WC} - E_{Co})f][(P_{Co} - \gamma_{WC} + 2tP_{Co}/D_{WC})f + \gamma_{WC} - 2tP_{Co}/D_{WC}]/D_{WC} \qquad (8)$$

This expression is just an equation relating the cobalt volume fraction and the WC grain size to the fracture strength of the WC–Co alloys.

3 DISCUSSION

3.1 Effect of cobalt volume fraction on σ_{bb}

To explain the phenomenon that the fracture strength σ_{bb} of the WC–Co alloys varies with the cobalt phase volume fraction, one can derive σ_{bb} with respect to f and the derivation is

$$\sigma'_{bb} = B\{E_{WC}(P_{Co} - \gamma_{WC} + 2tP_{Co}/D_{WC}) - (E_{WC} - E_{Co}) \cdot [(\gamma_{WC} - 2tP_{Co}/D_{WC}) + 2(P_{Co} - \gamma_{WC} + 2tP_{Co}/D_{WC})f]\}/2(D_{WC}\sigma_{bb})$$

Letting $\sigma'_{bb} = 0$ obtains the critical cobalt volume fraction:

$$f_c = E_{WC}/[2(E_{WC} - E_{Co})] - (\gamma_{WC} - 2tP_{Co}/D_{WC})/[2(P_{Co} - \gamma_{WC} + 2tP_{Co}/D_{WC}] \qquad (9)$$

It is easy to find that $\sigma'_{bb} > 0$ if $f < f_c$ and $\sigma'_{bb} < 0$ if $f > f_c$. These conclusions imply that the fracture strength increases with the cobalt volume fraction when the cobalt volume fraction is less than f_c, and reduces as the cobalt volume fraction is greater than its critical value f_c. These predications conform well to the experimental results shown in Fig. 1 for the WC–Co alloys with the same WC grain size. And the maximum value of the fracture strength is

$$(\sigma_{bb})_{max} = (B/D_{WC})^{1/2}[E_{WC}(P_{Co} - \gamma_{WC} + 2tP_{Co}/D_{WC}) + (E_{WC} - E_{Co})(\gamma_{WC} - 2tP_{Co}/D_{WC})]/[2(E_{WC} - E_{Co})(\gamma_{WC} + 2tP_{Co}/D_{WC})] \qquad (10)$$

From the expression, it can be seen that $(\sigma_{bb})_{max}$ decreases as the WC grain size D_{WC} increases, which agrees with the results found in Fig. 1.

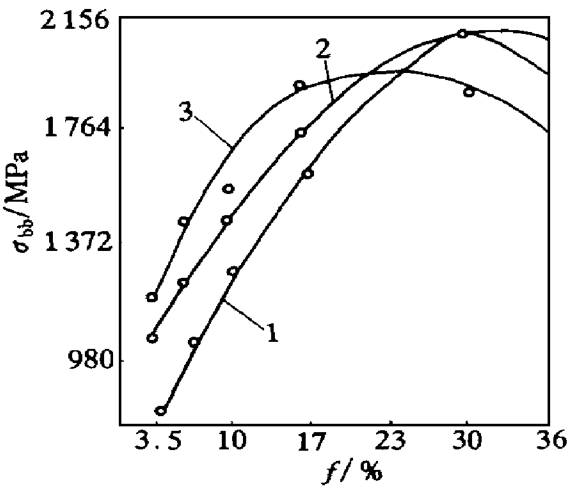

Fig. 1 Relationship between the bending strength and the cobalt volume fraction of the WC-Co alloys[4]

1 —D_{WC}= 1.64 μm; 2 —D_{WC}= 3.3 μm; 3 —D_{WC}= 4.95 μm

3.2 Effect of D_{WC} on the critical cobalt volume fraction

In formula (9), the critical value f_c of the cobalt volume fraction is only controlled by the WC grain size. Rewrite the expression of f_c as follows:

$$f_c = 1.2 - P_{Co}/[2(P_{Co} - \gamma_{WC} + 2tP_{Co}/D_{WC}] \qquad (11)$$

It is obvious that the value of f_c shifts to lower value as the WC grain size increases, as is in good agreement with the case shown in Fig. 2.

3.3 Effect of D_{WC} on σ_{bb}

The derivation of σ_{bb} with respect to D_{WC} is

$$\sigma'_{bb} = B[E_{WC} - (E_{WC} - E_{Co})f] \cdot [4tP_{Co}(1-f) - (fP_{Co} - f\gamma_{WC} + \gamma_{WC})D_{WC}]/(2D_{WC}^3\sigma_{bb})$$

Letting $\sigma'_{bb} = 0$ obtains

$$(D_{WC})_C = 4P_{Co} \cdot t(1-f)/[(P_{Co} - \gamma_{WC})f + \gamma_{WC}] \qquad (12)$$

It is easily found that $\sigma'_{bb} > 0$ as $D_{WC} < (D_{WC})_C$ and $\sigma'_{bb} < 0$ when $D_{WC} > (D_{WC})_C$. This means that the fracture strength of the alloys increases with D_{WC} as the WC grain size is less than $(D_{WC})_C$ and decreases as WC grain size is greater than $(D_{WC})_C$. In addition, the value of $(D_{WC})_C$ shifts to lower value when the cobalt volume fraction increases. These two cases agree well with the results found in Figs. 1 and 2.

The maximum value of σ_{bb}, corresponding to the value of $(D_{WC})_C$, is given by

$$(\sigma_{bb})_{max} = B[E_{WC} - (E_{WC} - E_{Co})f] \cdot [fP_{Co} + (1-f)\gamma_{WC}]/[8tP_{Co}(1-f)]^{1/2} \qquad (13)$$

This expression shows that $(\sigma_{bb})_{max}$ is mainly governed by the cobalt volume fraction of the WC-Co alloys, and increases with the cobalt volume fraction f, which can be proved by Fig. 2.

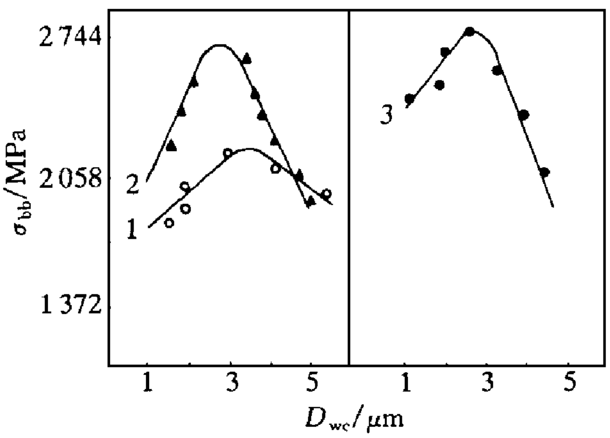

Fig. 2 Relationship between the bending strength and the WC grain size of the WC-Co alloys[5]

1—f = 0.19; 2—f = 0.25; 3—f = 0.30

4 SUMMARY

The present theory on the fracture strength of WC-Co alloys can perfectly explain the experimental results observed by the previous researchers, and a good functional agreement between the experimental results and the predications of this theory is easily obtained. This indicates that an exact equation characterizing the fracture strength of the WC-Co alloys may be established by considering discriminatingly the contributions of tungsten carbide and effective cobalt phase to the cemented carbide's fracture strength. WC grain size and cobalt volume fraction are two major microstructural factors determining the fracture strength of the WC-Co alloys. If the cobalt thickness of plastic deformation layer, t, and relative physical constants are obtained, the design of the microstructures of the WC-Co alloys will be possible. The calculation of the strength of the WC-Co alloys will be given in another paper.

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