Role of the Co Phase in Superplasticity for WC-Co Cemented Carbides

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Superplasticity and cavitation were investigated for WC-Co cemented carbides with the different WC grain sizes of 5.2 μm (C.G.), 1.7 μm (M.G.) and 0.7 μm (F.G.) by tensile tests at 1473 K. The largest elongation of 212% was obtained not for the F.G. specimen, but for the M.G. specimen. Furthermore, the flow stress was lower, the m value was larger and cavity formation was less for the M.G. specimen than for the F.G. specimen. The low elongation for the F.G. specimen is because less WC grains contacted the Co phase. This points out the importance of the distribution of the Co phase for superplasticity of the cemented carbides.

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1. Introduction

WC-Co cemented carbides are suitable for cutting tools, drilling tools and dies due to high stiffness, high strength, high toughness and so on.¹⁻³⁾ Recently, new trend of micro WC-Co tools has been reported^{4,5)} because miniaturization of devices is desirable in various fields such as information, bio, medical and environmental technologies. It is important to deeply understand the deformation and fracture mechanisms of WC-Co cemented carbides for development of macro- and micro-fabrication in the cemented carbides because the cemented carbides exhibit unique behavior due to the large difference in properties between the WC phase and the Co phase.

To date, there are many studies on mechanical properties of the cemented carbides.⁶⁻¹²⁾ It is known that deformation characteristics of the cemented carbides drastically change at about 973 K.^{7,8)} Sakuma⁹⁾ showed that the cemented carbide with the small WC grain size of 0.7 μm shows superplastic behavior at elevated temperatures. The Co phase increases the ductility and toughness at room temperature for the cemented carbides.^{10,11)} Hence, the Co phase is expected to contribute to an increase in superplastic elongation. In the present work, superplasticity and cavitation characteristics for the cemented carbides are investigated at 1473 K from the viewpoint of influence of the Co phase distribution.

2. Experimental Procedure

Three kinds of the cemented carbides were prepared; the WC-Co cemented carbide with the different WC grain sizes of 5.2 μm (C.G.), 1.7 μm (M.G.) and 0.7 μm (F.G.), where the Co content was 15 mass% for C.G., 10 mass% for M.G. and 15 mass% for F.G., respectively. Scanning electron micrographs of the cemented carbides annealed at 1473 K for 1.8 ks are shown in Fig. 1, where the specimens were polished mechanically and then etched with Murakami reagent. The

Co phase was not distributed uniformly, namely, there were the sites with no Co phase (Fig. 2(a)) and thick Co phase (Fig. 2(b)) between WC grains.

The WC grain size, d_{WC} , and the mean free path of Co phase, λ_{Co} , are given by¹³⁾

$$d_{\text{WC}} = \frac{4}{\pi} \cdot \frac{N_L}{N_s} \quad (1)$$

$$\lambda_{\text{Co}} = \frac{1-f}{N_L} \quad (2)$$

where N_L is the number of the carbides intercepted per unit length, N_s is the number of the carbides included per unit square and f is the volume fraction of carbide. The WC grain size and mean free path of Co phase of the cemented carbides are shown in Table 1. The λ_{Co} value increased with the WC grain size.

Constant crosshead velocity tensile tests were carried out at 1473 K in Ar to investigate superplastic properties of the cemented carbides, where the testing temperature of 1473 K is below the melting point of Co (= 1765 K). Tensile specimens had a gauge length of 25 mm, a gauge breadth of 4 mm and a gauge thickness of 1 mm. Cavitation in the deformed specimens was investigated by scanning electron microscope.

3. Results

The true stress-true strain curves at $6.7 \times 10^{-4} \text{ s}^{-1}$ are shown in Fig. 3, where the specimens are assumed to be deformed uniformly without necking. It should be noted that the M.G. specimen exhibited much larger elongation than the F.G. specimen. Besides, the flow stress for the M.G. specimen was lower than that for the F.G. specimen, though the F.G. specimen showed the lower flow stress than the C.G. specimen. In general, the flow stress for superplastic deformation decreases with a decrease in grain size.¹⁴⁾ However, the result in Fig. 3 showed that the superplastic flow stress does not necessarily decrease with decreasing WC grain size for WC-Co cemented carbides.

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Fig. 1 Scanning electron micrographs of the WC-Co cemented carbides annealed at 1473 K for 1.8 ks, (a) the C.G. specimen, (b) the M.G. specimen and (c) the F.G. specimen.

The variations in stress and elongation-to-failure at 1473 K as a function of strain rate for the cemented carbides are shown in Fig. 4, where the stress is the peak stress. It is well known that the strain rate sensitivity, m ($= d \ln \sigma / d \ln \dot{\epsilon}$, where σ is the stress and $\dot{\epsilon}$ is the strain rate), is high for superplastic flow.¹⁴⁾ The m value is the slope of the lines shown in Fig. 4(a). The high m values ≥ 0.4 were obtained for any specimens. In particular, the M.G. specimen showed the high m value of 0.8.

Large elongations of 186% and 212% were obtained at $6.7 \times 10^{-5} \text{ s}^{-1}$ for the C.G. specimen and at $6.7 \times 10^{-4} \text{ s}^{-1}$ for the M.G. specimen, respectively. However, it is of interest to note that for the F.G. specimen, the elongations in the range investigated were less than 40% at any strain rates, in spite of the smallest WC grain size.

Fig. 2 Non-uniform distribution of the Co phase in the F.G. specimen, (a) no Co phase site and (b) thick Co phase site between WC grains.

Table 1 The WC grain size, free path of Co phase and WC contiguity for the cemented carbides annealed at 1473 K for 1.8 ks.

Materials	d_{WC} , μm	λ , nm	C
Fine-grained cemented carbide	0.70	55.68	0.51
Medium-grained cemented carbide	1.65	199.33	0.31
Coarse-grained cemented carbide	5.17	533.43	0.27

Fig. 3 Stress-strain curves at 1473 K with $6.7 \times 10^{-4} \text{ s}^{-1}$ for the WC-Co cemented carbides.

4. Discussion

Superplastic elongation is often affected by cavitation. Hence, it is worthwhile to investigate cavities in the cemented carbides. Microstructures of the M.G. and the F.G. specimens deformed to $\epsilon = 0.15$ at $6.7 \times 10^{-4} \text{ s}^{-1}$ are

Fig. 4 The variations in stress and elongation-to-failure at 1473 K as a function of strain rate for the WC-Co cemented carbides, (a) stress and (b) elongation-to-failure.

shown in Fig. 5, where the tensile direction is horizontal. A lot of large cavities, which were elongated vertical to the tensile direction, were observed for the F.G. specimen (Fig. 5(c)). The same trend was observed at $6.7 \times 10^{-2} s^{-1}$ for the F.G. specimen. On the other hand, such large cavities were not observed at all for the M.G. specimen (Fig. 5(a)), though a few of micro cavities were observed (Fig. 5(b)). From Fig. 5(b), cavities were nucleated at the WC/WC interfaces. The trend was same as the other specimens and the previous works.^{15,16} Usually, for superplastic materials, cavitation tends to be enhanced for coarser grained materials than for the finer grained materials. However, as shown in Fig. 5, cavity formation was suppressed for the M.G. specimen, compared to the F.G. specimen, in spite of the larger WC grain size for the M.G. specimen.

The experimental results showed that the flow stress (at $6.7 \times 10^{-4} s^{-1}$) is lower, the m value is larger and cavity formation is less for the M.G. specimen than for the F.G. specimen, resulting in larger elongation for the M.G. specimen, in spite of the larger WC grain size. Thus, superplastic properties of the cemented carbides cannot be explained only by the WC grain size dependence. The fact that cavity formation was observed at the WC/WC boundaries, however, no cavities were nucleated at the WC/Co boundaries suggests that the distribution of the Co phase strongly affects the superplastic properties. The WC contiguity, which is one of parameters representing the number of the WC grain in direct contact with the WC grain without the Co phase, is given by¹⁷⁾

$$C_{WC} = \frac{2N_{WC/WC}}{N_{WC/Co} - 2N_{WC/WC}} \quad (3)$$

Fig. 5 Microstructures of the specimens deformed to $\epsilon = 0.15$ at 1473 K with $6.7 \times 10^{-4} s^{-1}$, (a) the M.G. specimen (low magnification), (b) the M.G. specimen (high magnification) and (c) the F.G. specimen (low magnification), where the tensile direction is horizontal.

where C_{WC} is the WC contiguity, $N_{WC/WC}$ is the number of interfaces between WC grains intercepted per unit length and $N_{WC/Co}$ is the number of interfaces between WC grains and Co phase intercepted per unit length. The C_{WC} values of the C.G., M.G. and F.G. specimens were 0.27, 0.31 and 0.51, respectively, as listed in Table 1. It should be noted that the C_{WC} value of the F.G. specimen was larger than those of the others, indicating that the number of the WC grains contacting the Co phase is fewer for the F.G. specimen than for the others. Therefore, it is likely that the low elongation for the F.G. specimen is due to less WC grains contacted the Co phase. Thus, the importance of the distribution of the Co phase is pointed out for superplasticity of the cemented carbides, namely, grain boundary sliding is enhanced by the presence of the Co phase between the WC grains, resulting in low flow stress and high m value. Besides, the Co phase serves to relax the stress concentrations which are caused by grain boundary sliding, resulting in suppression of cavitation, as shown in Fig. 5. Thus, the Co phase plays a vital role in superplasticity for the cemented carbides.

5. Conclusions

- (1) Superplasticity and cavitation were investigated at 1473 K for WC-Co cemented carbides with the different WC grain sizes of 5.2 μm (C.G.), 1.7 μm (M.G.) and 0.7 μm (F.G.).
- (2) The largest elongation of 212% was obtained not for the F.G. specimen, but for the M.G. specimen. Further-

more, the flow stress was lower, the m value was larger and cavity formation was less for the M.G. specimen than for the F.G. specimen.

- (3) The low elongation for the F.G. specimen is due to less WC grains contacted the Co phase. This points out the importance of the distribution of the Co phase for superplasticity of the cemented carbides.

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