The Bend Deformation of WC-Co Cemented Carbides at Temperatures up to 1273 K*

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The bend deformation characteristics of WC-Co cemented carbides were investigated in the temperature range from room temperature to 1273 K by measuring load-deflection curves and examining the structural change due to deformation, in relation to cobalt content, tungsten carbide particle size, domain (grain) size of binder phase and carbon content. The cemented carbides were almost elastically deformed up to fracture at room temperature, but they became to be plastically deformed at high temperatures above about 873 K. The high temperature deformation, however, was not composed merely of a true plastic deformation, because stable cracks were frequently formed at high stress levels. Effects of the above factors on the deformation characteristics at temperatures below 873 K can be explained mainly from the viewpoint that the binder phase is dispersion-hardened and solid-solution hardened. However, the effects of particle size and carbon content at high temperatures tended to be reverse to those at low temperatures. This is explained by the dynamic recovery of binder phase occurring at high temperatures. The deformation at high temperatures and high stress levels was found to be suppressed with increase in domain size. In this paper, the relation between transverse-rupture strength and deformation characteristics was also briefly mentioned.

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I. Introduction

The transverse-rupture strength of WC-Co cemented carbides has so far been investigated by the authors in the temperature range from room temperature to 1273 K, taking account of the types and sizes of fracture source, as a function of cobalt content, particle size of tungsten carbide, domain (grain) size of binder phase, carbon content, strain rate, etc.⁽¹⁾⁻⁽⁷⁾. Thus it seems that the effects of these factors on the strength of cemented carbides have been nearly made clear. However, for the practical use of various cemented carbides, further knowledge on their deformation characteristics is greatly needed. The present study was undertaken to clarify the bend deformation characteristics of WC-Co cemented carbides, particularly at high temperatures between 873 and 1273 K, as a function of the above factors. In addition, the relation between deformation characteristics and transverse-rupture strength was also considered.

II. Experimental Procedure

By using commercially available tungsten carbide (WC) powders of different particle sizes from 1.5 to 6.0 μm and cobalt powder of 1.5 μm , the WC-(10-30%)Co specimens with different carbon contents and particle sizes (1.3-5.5 μm) were prepared by vacuum-sintering at 1623-1673 K for 3.6-7.2 ks. The cooling rate after sintering was generally $(3-4) \times 10^{-1}$ K/s, and it was lowered to 8×10^{-2} K/s to obtain the specimen with coarse domains of binder (γ) phase. Here, a domain of γ phase means a region in which γ phase has an identical crystallographic orientation⁽⁸⁾. Table 1 shows WC-(10-30%)Co specimens mainly used, and their WC particle size, carbon content and γ domain size.

After specimens were ground by using a diamond-wheel to obtain JIS test pieces ($4.0 \times 8.0 \times 24.0$ mm³), they were subjected to three-point bend tests (span, 20.0 mm) to get load-deflection (P-d) curves[†] and transverse-rupture strength (TRS)^{††}. The bend tests were per-

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†,†† The P-d curves were always calibrated by use of the curves obtained in blank tests. In calibrated P-d curves which will be shown later, the load of 1 kN and the deflection of 0.1 mm correspond to the stress of 0.234 GPa and the strain of 0.6%, respectively, assuming that specimens are perfectly elastic. The values of TRS were calculated from the maximum load in P-d curves.

Table 1 Specimens used, and their particle size of tungsten carbide (WC), carbon content and domain size of binder (γ) phase. "H", "M" and "L" show high, medium and low carbon contents, respectively.

Specimens	WC particle size (μm)	Carbon content	γ domain size (μm)
WC-10% Co	1.3	M	170, 300
	1.6	H	210
	1.6	L	390
	3.8	H	160
	3.8	M	140, 270
	3.8	L	280
	5.5	H	160
	5.5	L	230
WC-20% Co	1.3	M	300, 550
	1.6	H	420
	1.6	L	660
	3.8	H	240
	3.8	M	250, 490
	3.8	L	380
	5.5	H	280
	5.5	L	310
WC-30% Co	1.3	M	510, 1200
	3.8	M	400, 720

formed in the temperature range from room temperature (r.t.) to 1273 K, particularly in vacuum at temperatures above 873 K. The crosshead speed was generally 8.3×10^{-6} m/s. After the tests, changes in structure, stable crack formation, etc., were examined on the tension-side surface of specimens. Based on the results of P-d curves and structural examinations, the deformation characteristics of WC-

Fig. 1 Effects of Co content, WC particle size and domain size on bending load-deflection (P-d) curves of WC-Co medium carbon alloys. "F" and "C" show specimens with fine and coarse domains, respectively. Test temperature: room temperature. Specimen size, $4.0 \times 8.0 \times 24.0$ mm³; Span, 20.0 mm; Crosshead speed, 8.3×10^{-6} m/s.

Co cemented carbides were discussed in relation to the test temperature, Co content, WC particle size, domain size and carbon content

Fig. 2 The same as Fig. 1. Test temperature: 873 K.

Fig. 3 The same as Fig. 1. Test temperature: 1073 K.

of specimens. A brief consideration was given also to the relation between deformation characteristics and values of TRS.

III. Experimental Results

Figures 1–4 show examples of P-d curves obtained at r.t., 873, 1073 and 1273 K, respectively, for WC-(10–30%)Co medium carbon specimens with particle sizes of 1.3 and 3.8 μm .

The domain size is varied in each specimen having different Co contents and particle sizes. First, effects of test temperature and Co content are mentioned. The curves at r.t. are approximately linear, particularly in low Co specimens, up to the load of fracture, showing that the deformation of specimens is nearly elastic. On the other hand, the slopes of curves at high temperatures become gentle with increasing test temperature and Co content. This indicates that specimens are plastically deformed in a considerable amount under these conditions. Values of elastic modulus obtained from the slope of curves at low stresses varied reasonably with changes in test temperature and Co content, but they did not depend on carbide particle size and domain size.

Next, effects of WC particle size and domain size are described. The amount of deformation becomes larger below 873 K in the specimens with larger particles as well as higher Co content. However, it is noteworthy that the amount of deformation at 1273 K becomes smaller in the specimens with larger particles at a fixed

Fig. 4 The same as Fig. 1. Test temperature: 1273 K.

Co content. The curves at 1073 K show a complicated feature; for instance, the slope of curves of 10% Co specimens with large particles is steeper at low stresses, but gentler at high stresses, than that of the specimens with small particles. It is seen that curves at r.t. are hardly affected by domain size (Fig. 1), but this is not the case above 873 K; the deformation above 873 K is clearly suppressed in the specimens with coarse domains. Such a suppression of deformation is enhanced with increasing test temperature and Co content and decreasing particle size.

Figures 5 and 6 show the effect of carbon content on P-d curves at 873 and 1273 K, respectively, for WC-(10, 20%)Co specimens with particle sizes of 1.6 and 3.8 μm . The amount of deformation at 873 K is smaller in a low carbon alloy than in a high carbon alloy, and the tendency becomes more remarkable as Co content and particle size increase. Results obtained at 873 K were nearly the same as those obtained at r.t. The carbon effect as stated above, however, does not always apply at 1273 K. That is, in the specimens with small particles, the carbon effect is reversed in the stress range up to considerably high stresses.

It is seen in Figs. 1-6 that P-d curves of specimens having a fixed Co content branch into two curves at a certain load, according to the differences in particle size, domain size and carbon content, respectively. The branching load relating to the difference in particle size is nearly the same as that regarding carbon con-

Fig. 5 Effect of carbon content on P-d curves of WC-(10, 20%)Co alloys with particle sizes of 1.6 and 3.8 μm . "H" and "L" show high and low carbon alloys, respectively. Test temperature: 873 K.

tent, but it is lower than that regarding domain size. In other words, the effect of domain size on P-d curves occurs at higher stresses than the other two effects.

Now, the values of TRS are taken up. The dependences of the TRS on Co and carbon contents did not change in the temperature range from r.t. to 1273 K; TRS increased with decreasing Co and carbon contents, independently of test temperature. However, dependences of the TRS on WC particle size and domain size tended to be reversed between low and high temperatures. At low temperatures, TRS increased with decreasing particle size, while at 1273 K it increased with increasing

Fig. 6 The same as Fig. 5. Test temperature: 1273 K.

Fig. 7 Effects of several factors on transverse rupture strength of WC-Co alloys at 1273 K. (a) effects of WC particle size, and Co and carbon contents; (b) effects of Co content, and particle and domain size.

particle size in the range less than 4.0–5.0 μm . Figure 7(a) shows TRS at 1273 K for WC-(10, 20%)Co high and low carbon specimens, in relation to the particle size. Maximum values of the TRS are obtained at the particle sizes of about 4.0 and 5.0 μm in high and low carbon alloys, respectively, independently of Co content. On the other hand, the TRS increased with domain size above 873 K in contrast with the result at low temperature⁽²⁾. An example of the dependence of the TRS on domain size at 1273 K is shown in Fig. 7(b), as a function of Co content. In this figure, the TRS of medium carbon specimens with particle sizes of 1.3 and 3.8 μm is indicated.

It was found that, as the deformation at low stress levels was suppressed, values of the TRS tended to increase. However, there are a few exceptions. In the case of WC-30% Co alloys, fine- and coarse-dominated specimens with particle size of 3.8 μm showed a smaller amount of deformation at 1273 K at low stresses than the specimens with particle size of 1.3 μm , but the former specimens were not always higher

in the TRS than the latter (Figs. 4 and 7(b)). Results obtained at 1273 K in WC-(10, 20%)Co high and low carbon specimens with a small particle size of 1.6 μm (Figs. 6 and 7(a)) also belong to an exception.

Then microstructural changes of specimens due to bend deformation were examined on the tension-side surface near the span center. Photograph 1(a) shows domains of γ phase before deformation for WC-30% Co specimen. Here, the specimen surface was polished and then etched in 2% HNO_3 aqueous solution to reveal the domain structure. Subsequently, this revealed domain structure was erased by slight polishing of the surface, and then the specimen was loaded to fracture at 1273 K. The surface structure of the fractured specimen is shown in Photo. 1(a'). Photographs 1(a) and (a') were taken of the same specimen area. From these photographs, it is clearly seen that unevenness was formed on the deformed specimen surface and that each area denoted by A', B', ... in

Photo. 1 Change in structure on tension-side surface due to bend deformation. (a) domains which are revealed before deformation; (a') surface structure after deformation. WC-30% Co alloy, used. Test temperature: 1273 K.

Photo. 1(a') corresponds well with each γ domain denoted by A, B, ... in Photo. 1(a). It is also clear that each of the domains behaves just as a unit region of deformation. The unevenness became pronounced when the amount of deformation at low stresses increased, or when a high Co alloy specimen was tested at high temperatures.

It was found that stable cracks were formed mainly at the domain boundaries with marked or pronounced unevenness. An example of the relation between stable crack formation and domain boundaries is shown in Photo. 2(a, a') for a WC-30% Co specimen deformed at 1273 K. Photograph 2(a) shows a domain observed after deformation (refer to Photo. 1(a')) and Photo. 2(a') shows stable cracks revealed out by slight polishing of the surface shown in (a). As the load increased, the stable cracks grew large, preferentially along the domain

boundaries. The stable cracks were easily formed at high temperatures. It was found that the crack formation load was higher for the alloy showing a smaller amount of deformation at low stresses, and that it was nearly equal to the branching load regarding domain size. Then, it is noticeable in Figs. 2-4 that above the crack formation load the slope of P-d curves becomes gentler and a large amount of deformation is produced. This means that the high temperature deformation of cemented carbides does not take place merely by a true plastic deformation. In other words, the apparent deformation due to the stable crack formation contributes to the deformation of cemented carbides at high temperatures. Based on these results, the foregoing description that cemented carbides are plastically deformed in a considerable amount at high temperatures must be corrected.

The fact that stable cracks grew preferentially along the domain boundaries should be noted, because the growth of stable cracks is retarded in the specimen with coarse domains⁽⁷⁾. Thus the following result is easily explained; the specimen with coarse domains showed a smaller amount of deformation and a higher TRS at high temperatures above 873 K. Whether the domain boundary sliding or the interface sliding between WC particles occurred during deformation was studied. No proof for the slidings was obtained at any temperature. The formation of microvoids was not observed.

IV. Discussion

In the preceding section, the deformation characteristics of WC-Co cemented carbides were mainly described in relation to test temperature, Co content, WC particle size, carbon content and γ domain size. Among the results obtained, the effects of particle size, carbon content and domain size on deformation characteristics are considered to be especially important.

The specimens with small WC particles at a fixed Co content generally showed a low deformability and a high TRS below 873 K. This result can be understood by considering that γ phase of cemented carbides is dispersion-

Photo. 2 Relation between domain boundaries and stable crack formation. (a) a domain observed after deformation (refer to Photo. 1(a')); (a'), stable cracks along or near boundaries, revealed after slightly polishing the deformed surface. WC-30% Co alloy, used. Test temperature: 1273 K.

hardened by WC particles. However, the deformation at high temperature of 1273 K was suppressed in the specimens with larger particles. Then, WC-10% Co alloy specimens with particle sizes of 1.3 and 3.8 μm were loaded at 1273 K and unloaded immediately after the load reached a fixed value. After unloading, the specimens were rested at the same temperature for different times from 0 to 300 s, and then reloaded. The P-d curves obtained in the first loading and reloading are shown in Fig. 8. From this figure, it is evident that reloading curves R_1 , R_2 and R_3 do not follow the first loading curve F in both specimens with small and large particles, and the slopes of reloading curves are always steeper. The slope of reloading curve becomes gentle as the resting time increases. These results indicate that the internal strains are stored in the specimen during the first loading and recover during the resting time. This recovery is associated with that of γ phase. When the reloading curves of both specimens having the same resting times are compared, it is evident that the recovery is more suppressed in the specimen with larger particles, suggesting that the dynamic recovery of γ

phase during loading tests becomes more difficult in the specimen having larger particles. This is quite natural because climbing distances of dislocations piled up against WC particles increase in the specimen having larger particles. The complicated characteristics of deformation at 1073 K (Fig. 3) are understandable, taking into account that this test temperature is intermediate between 873 and 1273 K.

The effect of carbon content is discussed in the following. The deformation below 873 K was more suppressed in the low carbon specimen (Fig. 5). This is probably due to the fact that the lowering of carbon content increases the amount of dissolved tungsten in γ phase⁽⁹⁾, making the γ phase more solid-solution hardened. The carbon effect at high temperature in the specimens with large particles was the same as that at low temperature. But, in the specimens with small particles, the effect was reversed at 1273 K as before mentioned. Then P-d curves affected by the crosshead speed (CHS) were examined for WC-10% Co high and low carbon alloys with particle sizes of 1.6 and 5.5 μm . Results obtained are shown in Fig. 9. In this figure, the results of WC-10% Co alloys having 1.6 μm , shown in Fig. 6, are referred to for comparison. In the specimens

Fig. 8 P-d curves of specimens with particle sizes of 1.3 and 3.8 μm , which are influenced by reloading. Resting times after unloading are changed. "F", the first loading curve; " R_1 ", " R_2 " and " R_3 ", reloading curves after resting for 0, 40 and 300 s, respectively.

Fig. 9 Effect of crosshead speed on P-d curves of high and low carbon alloys with particle sizes of 1.6 and 5.5 μm .

of $5.5\text{ }\mu\text{m}$, the low carbon alloy shows a smaller amount of deformation than the high carbon alloy, independently of stresses and CHS. In contrast with this, in the specimens of $1.6\text{ }\mu\text{m}$, the low carbon alloy shows a larger amount of deformation at low stresses at common CHS of $8.3 \times 10^{-6}\text{ m/s}$, but this does not apply at high CHS of $8.3 \times 10^{-5}\text{ m/s}$. These results will explain the fact that the carbon effect was reversed in the stress range up to considerably high stresses, because the dynamic recovery will occur more easily in low carbon alloy, when the particle size is small and CHS is common.

As to the domain size effect, the following results at high temperatures are greatly interesting. The deformability of coarse-dominated specimens was lower than that of fine-dominated specimens. Cemented carbides were deformed as the result of deformation of individual domain, so that the unevenness corresponding to the domain was produced on the specimen surface. Stable cracks formed at the boundaries of uneven domains and propagated preferentially along the boundaries with increase in the stress. Branching loads in P-d curves due to the difference in domain size were higher than those due to particle size and carbon content.

Since the low deformability in coarse-dominated specimens has already been clarified in view of stable crack propagation, discussion on the other results is made in the following. It is generally accepted that the deformation of cemented carbides is induced by the deformation of γ phase and that the deformation of γ phase is affected by WC particle size (or mean free path of γ phase) and carbon content at a fixed Co content, as also described in this study. However, according to the present result, it has become clear that the deformation of γ phase is affected also by the crystallographic orientation of γ phase, the effect of which is very much large. Consequently, the unevenness corresponding to the domain is formed on the specimen surface. With the formation of unevenness, stress concentration at some domain boundaries might increase anomalously, so

that the stable cracks are generated at the boundaries and subsequently the propagation takes place along the boundaries with increase in stress. At this stage, the domain size effect becomes apparent on P-d curves. Thus it is natural that the branching load by the domain size effect is higher than those by other factors.

It can be understood that the TRS tended to increase in the alloy showing a smaller amount of deformation at low stresses, because in such an alloy the load for the stable crack formation was generally higher. The exceptional result of WC-30% Co alloys (Figs. 4 and 7(b)) is explained by considering that the domain size is especially large in the coarse-dominated specimen with the particle size of $1.3\text{ }\mu\text{m}$ (Table 1), leading to a strong retardation of the stable crack growth in the specimen.

These effects of several factors on the deformation characteristics, which have been made clear for WC-Co cemented carbides in this study, would dominate for the other commercially available cemented carbides. Therefore, the present results are considered to contribute to the evaluation of the deformation characteristics of cemented carbides.

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