High-Temperature Tensile Ductility in WC-Co Cemented Carbides

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High-temperature tensile deformation in WC-Co was investigated at temperatures between 1150 °C and 1250 °C. The flow stress is sensitive to temperature, strain rate, volume fraction of binder, and the addition of other carbides. The stress-strain rate relationship is divided into three regions at each temperature as in superplastic metals. A large tensile elongation over 100 pct was first obtained in WC-6Co and WC-13Co (wt pct) at temperatures of 1200 °C. Contrary to superplastic metals, the largest tensile elongation is not obtained in region II but on the border of regions I and II. The failure mode changes from necking in region I to sharp cracking in region II.

I. INTRODUCTION

The compounds WC-Co have extensively been used for wear and cutting tools at elevated temperatures. Thus, information on high-temperature strength and plastic flow behavior in cemented carbides is very important for practical use. However, it is not so easy to find a rate controlling mechanism for plastic flow in this material, because the flow stress at elevated temperatures depends on various factors such as carbide grain size, binder content, addition of other carbides, and so on.[1-12]

It has been clarified by creep testing or compression testing that the flow stress-strain rate relationship in cemented carbides is given by a sigmoidal curve at a constant temperature as in superplastic metals.[9,11,13-16] Three different mechanisms must be operating at each temperature depending on strain rate. Judging from the experimental data, it is expected that the superplastic flow occurs in region II.

The present article aims to report the high-temperature tensile ductility in WC-Co at temperatures between 1150 °C and 1250 °C.

II. EXPERIMENTAL PROCEDURES

The chemical composition and carbide grain size of the materials used in the present study are given in Table I. The WC powders with an average grain size of 0.88 μm supplied by Japan New Metals Co., Ltd. (Toyonaka City, Osaka, Japan) were used for starting materials. The alloys were prepared by ball milling the powders of WC, Cr3C2, VC, and Co in ethanol together with cemented carbide balls for 24 to 48 hours. The slurry was dried and granulated. These granules were pressed into bars in a cemented carbide die under a pressure of 20 MPa, and then cold isostatically pressed under a pressure of 130 MPa in a rubber tube. Sintering was carried out at temperatures between 1380 °C and 1430 °C for 1 hour in a pressure range of 10⁻¹ to 10⁻² torr. The carbide grain size was controlled by choosing the sintering temperature. The bulk density of sintered bodies was measured by the Archimedes method. The tensile specimens with 2 x 2 x 13.3-mm³ gage length were prepared from the sintered samples by cutting and grinding.

High-temperature tensile tests were made using an Instron-type mechanical testing machine SHIMADZU AG-5000C equipped with a high-temperature furnace. Hexagonal BN powders were sprayed on the test specimen in order to avoid sticking of the specimen with SiC rods. The specimen was set inside a quartz tube in Ar atmosphere and heated with an infrared image furnace ULVAC RHE-45. The tests were carried out in a temperature range of 1150 °C to 1250 °C and in an initial strain rate range of 6.3 x 10⁻⁴ to 6.3 x 10⁻³ s⁻¹. To examine the effect of the testing atmosphere on the tensile deformation behavior, several samples were deformed at 1200 °C in a high vacuum (<10⁻⁴ torr) at NRIM (Tsukuba, Japan).

Microstructures before and after deformation were examined with an optical microscope and a scanning electron microscope (SEM) JEOL® JSM-5200. Specimens for SEM examination were chemically etched with a Murakami solution. The carbide grain size was estimated from the mean linear intercept length of carbides by a conventional metallographic technique.

III. RESULTS AND DISCUSSION

A. High-Temperature Plastic Flow Behavior

Figure 1 shows the stress-strain curves of WC-6Co (0.78 μm) alloy deformed with an initial strain rate of 2.5 x 10⁻⁴ s⁻¹, and Figure 2 shows those of WC-13Co (0.70 μm) with an initial strain rate of 6.3 x 10⁻⁴ s⁻¹. The flow stress is highly dependent on the deformation temperature. In both alloys, tensile elongation reaches a maximum at an intermediate deformation temperature of 1200 °C and is 79 and 103 pct of nominal strain in WC-6Co and WC-13Co, respectively. This is the largest elongation achieved in WC-Co so far.

It is noted that the stress-strain behavior is different between WC-6Co and WC-13Co. That is, WC-6Co (10 vol pct Co) shows a sluggish decrease of flow stress after yielding, whereas WC-13Co (20 vol pct Co) exhibits fairly abrupt reduction in flow stress. The rapid decrease in flow...
Table I. The chemical composition and grain size of the materials used in the present study

<table>
<thead>
<tr>
<th>Composition</th>
<th>Grain Size (μm)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC-6Co</td>
<td>0.78</td>
<td>15.05</td>
</tr>
<tr>
<td>WC-13Co</td>
<td>0.70</td>
<td>14.55</td>
</tr>
<tr>
<td>WC-6Co-1Cr₃C₂-0.5VC</td>
<td>0.76</td>
<td>14.92</td>
</tr>
</tbody>
</table>

stress after yielding is attributed to necking in WC-13Co, as will be discussed later.

Figure 3 shows the strain rate dependence of flow stress in WC-13Co deformed at 1200 °C with initial strain rates ranging from 6.3 × 10⁻² to 6.3 × 10⁻³ s⁻¹. As strain rate slows down, the stress for plastic flow decreases. However, the maximum elongation in this material is obtained not at the lowest strain rate of 6.3 × 10⁻³ s⁻¹ but at the intermediate strain rate of 6.3 × 10⁻⁴ s⁻¹.

Figure 4 is a comparison of stress-strain curves between WC-6Co (0.78 μm) and WC-6Co-1Cr₃C₂-0.5VC (0.76 μm) at 1200 °C and a strain rate of 2.5 × 10⁻⁴ s⁻¹. The addition of other carbides such as Cr₃C₂ and VC was made for retarding the carbide grain growth during liquid phase sintering. The two materials show quite different behavior in stress-strain curves. A small addition of Cr₃C₂ and VC gives rise to the marked increase in flow stress and severe decrease in tensile elongation. The increment of flow stress may be caused by the presence of Cr and V in the binder phase. The reduction in tensile ductility in WC-Co by an addition of Cr₃C₂ and VC must be caused by the flow stress increase.

Figure 5 shows the photographs of (a) WC-6Co and (b) WC-13Co specimens failed in tension in a high vacuum (<10⁻⁵ torr). The testing condition of each material is that the maximum elongation is recorded. The tensile elongations obtained are 108 and 137 pct in WC-6Co and WC-13Co, respectively. The tensile elongation is improved by changing the testing atmosphere from Ar gas to vacuum, and neck formation is more striking in WC-13Co than in WC-6Co.

Figure 6 is a plot of log flow stress as a function of log strain rate in WC-6Co with a grain size of 0.78 μm at three temperatures. The plot at each temperature is not given by a linear relationship but is convex downward. With increasing deformation temperature, the curve shifts toward the right side, i.e., to the high strain rate side. It has been reported that the log stress against log strain rate relationship is represented by a sigmoidal curve in high-temperature compressive deformation of WC-Co [13-16] and also in creep deformation of the material [9,11]. The relationship can be divided into three regions, the low, intermediate, and high strain rate regions, which are termed regions I, II, and III, respectively. The logarithmic plot of flow stress against strain rate is approximated to be a straight line in each region. Judging from the previous data, it is expected that