ELSEVIER

International Journal of Refractory Metals & Hard Materials 17 (1999) 39–44

International Journal of
REFRACTORY METALS
& HARD MATERIALS

Influence of temperature, grain size and cobalt content on the hardness of WC–Co alloys

Yu.V. Milman [a], S. Luyckx [b,c], IT Northrop [d]

[a] *Institute of Problems in Materials Science, Kiev, Ukraine*
[b] *School of Process and Materials Engineering, University of the Witwatersrand, Johannesburg, South Africa*
[c] *Mattek, CSIR, Pretoria, South Africa*
[d] *Boart Longyear Research Centre, Krugersdorp, South Africa*

Received 9 March 1998; accepted 14 July 1998

Abstract

The Vickers hardness of WC–Co alloys has been measured at temperatures ranging from −196 to 900°C. The cobalt content of the alloys ranged from 10 to 24 vol% and the grain size from 0.5 to 2.3 μm. It was found that, at all cobalt contents and all temperatures, the decrease in hardness with increasing grain size can be approximated by a Hall–Petch type relationship. Up to about 600°C the decrease in hardness with increasing temperature appears to be due mostly to the decrease in the intrinsic hardness of the individual phases. Above 600°C the decrease in hardness appears to be due mostly to easier slip transfer across grain boundaries. Finer grained alloys have been found to preserve their hardness at high temperature better than coarser grained alloys, at all cobalt contents.

Keywords: Vickers hardness; Cobalt; Slip transfer

1. Introduction

It has been shown [1] that within the temperature range −196 to 900°C the hardness of WC–10 vol% Co alloys decreases with increasing WC grain size according to a relationship of the following type:

$$H = H_0 + K_y d^{\frac{1}{2}} \qquad (1)$$

i.e. according to a Hall–Petch type relationship, where H is the hardness of the alloy, d the mean WC grain size and H_0 and K_y are functions of the properties of the individual phases, and of the composition and the microstructural parameters of the alloy [1].

The results reported in Ref. [1], therefore, show the effect of temperature and grain size on the hardness of WC–10 vol% Co. The present work extends the previous investigation to WC–Co alloys of three different cobalt contents, in order to quantify the effect on hardness of cobalt content, as well as temperature and grain size.

2. Method

The samples used for this investigation are disks of 14 mm diameter and 3 mm thickness. The WC grain size distribution and the mean grain size for all specimens are determined by means of a Leica QSOOMC Image Analyser, and are shown in Fig. 1. The composition and grain size of the grades investigated are given in Table 1.

The Vickers hardness is measured at the following temperatures: −196, −80, 20, 200, 300, 400, 500, 600, 700, 800 and 900°C. In the range 20–900°C the hardness is measured using a 60 N load in a BIM-1 installation [2] in a vacuum of about 10^{-3} Pa. In this installation the load on the Vickers indenter is determined by the total weight of the moving column, weights and indenter. The samples and indenter are heated by means of a molybdenum heater. In the range −196 to 400°C the hardness is measured in an Instron type mechanical testing machine with the sample immersed in the cooling liquid [3] and at a 200 N load. The cooling liquid is a mixture of liquid nitrogen and petroleum ether.

3. Results

Although the samples were prepared with the intention of producing three sets of grades of equal grain sizes but different cobalt contents, Fig. 1 shows that in the

0263-4368/99/$ – see front matter
PII: S 0 2 6 3 - 4 3 6 8 (9 8) 0 0 0 3 8 - 9

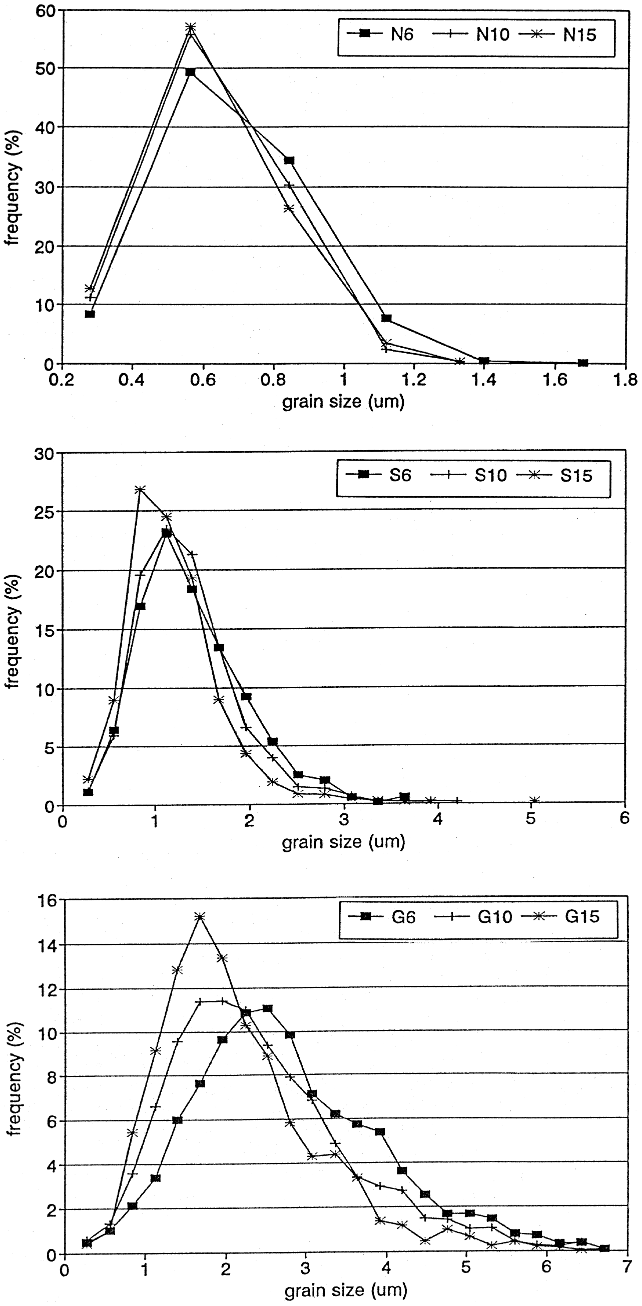

Fig. 1. Grain size distribution of the three sets of WC–Co grades tested, described in Table 1.

Table 1
Composition of grain size of the WC–Co grades investigated

C–Co grades	Co wt%	WC vol% (V_{wc})	Mean grain size, d (μm)
N6	6	90	0.54
N10	10	84	0.47
N15	15	76	0.48
S6	6	90	1.26
S10	10	84	1.20
S15	15	76	1.05
G6	6	90	2.62
G10	10	84	2.28
G15	15	76	2.00

case of the G grades the mean grain size ranged from 2.00 to 2.60 μm.

The results of the hardness tests are summarised in Fig. 2. The graphs in Fig. 2(a) illustrate the dependence of hardness on temperature and cobalt content, and the graphs in Fig. 2(b) illustrate the dependence of hardness on temperature and grain size. Fig. 3 shows the dependence of hardness, H, on grain size, d, at different temperatures in Hall–Petch coordinates. All of the lines in Fig. 3 can be represented by Eq. (1). The regression coefficients of the lines in Fig. 3 are all higher than 0.95 and mostly higher than 0.99.

Figures 4 and 5 show the dependence on temperature and cobalt content of the parameters H_0 and K_y in Eq. (1). Up to 600°C, H_0 decreases with increasing temperature more rapidly than K_y and the opposite is true above 600°C. They also show that K_y seems to depend on cobalt content more markedly than H_0.

Fig. 6 is a plot of the ratio between the hardness of WC–Co at 600°C and the hardness at room temperature (H_{600}/H_{20}) versus grain size at the three cobalt contents tested. It shows that the ratio is highest at the lowest cobalt content at all temperatures and at all grain sizes, and that it is higher at finer grain sizes at all cobalt contents. Fig. 7 shows that the ratio between the hardness of the finest and the coarsest grades tested ($H_{0.5}/H_{2.3}$) increases with increasing temperature at least up to 600°C.

4. Discussion and conclusions

The results reported above confirm that the hardness of WC–Co decreases with increasing temperature, increasing cobalt content and increasing WC grain size. In addition, they show that Eq. (1) is a good approximation of the relationship between hardness and grain size at all temperatures and cobalt contents tested.

In order to interpret the results, we use results obtained in previous studies by these authors and by Lee and Gurland [1,4]. The two parameters appearing in Eq. (1) can be related to the volume fraction, V_{wc}, and the contiguity, C, of the carbide phase in the following way [1]:

$$H_0 = H_{owc}V_{wc}C + H_{om}(1 - V_{wc}C) \qquad (2)$$

$$K_y = K_{owc}V_{wc}C + K_{om}(1 - V_{wc}C)B^{-\frac{1}{2}} \qquad (3)$$

where

$$B = \frac{1 - V_{wc}}{V_{wc}(1 - C)}$$

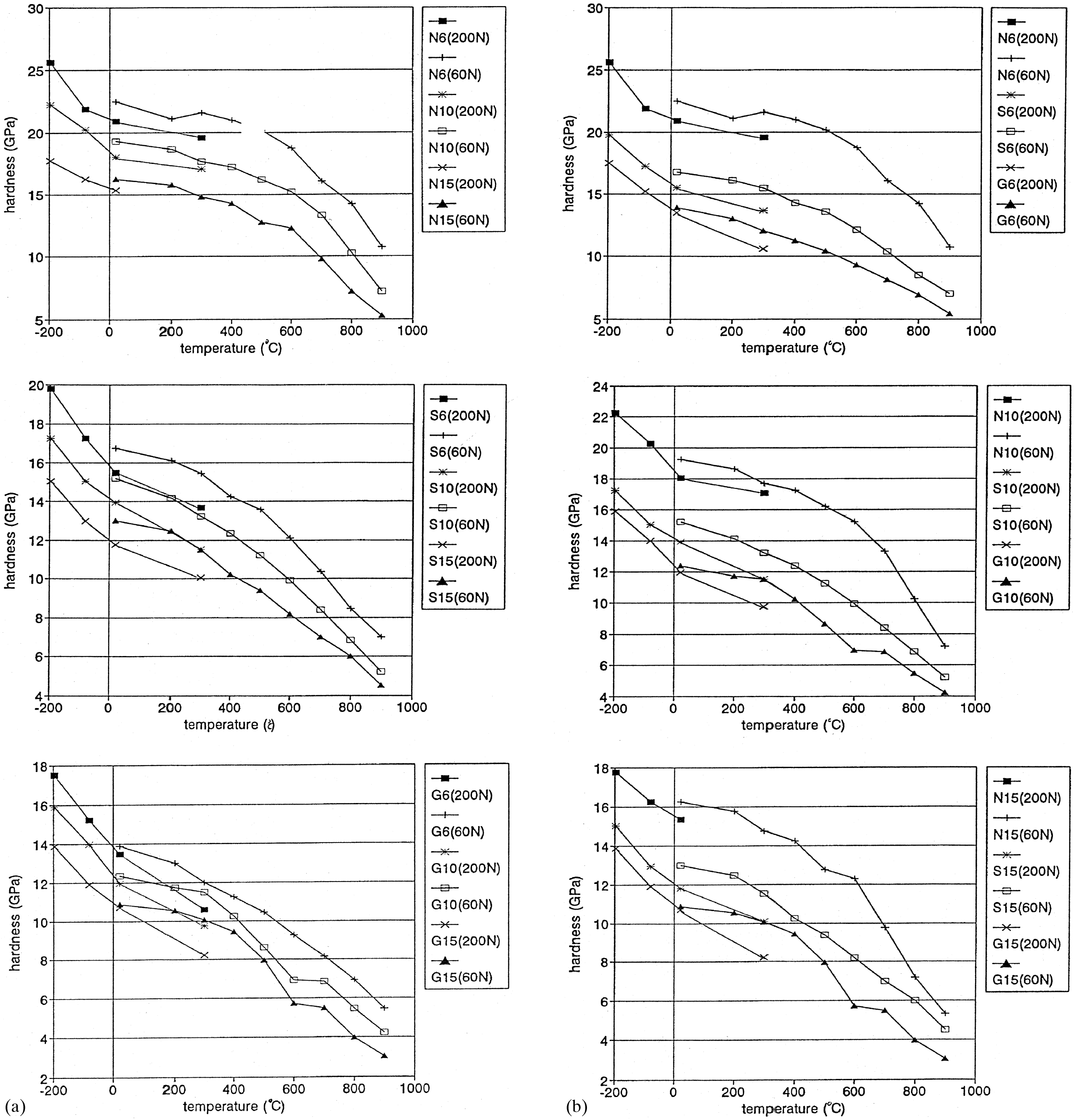

Fig. 2. Plots of hardness versus temperature of the three sets of WC–Co grades tested. (a) Dependence of hardness on temperature when the cobalt content varies and the grain size is constant. (b) Dependence of hardness on temperature when the grain size varies and the cobalt content is constant.

and

V_{wc} = volume fraction of WC
C = contiguity

H_{owc} and K_{owc}, H_{om} and K_{om} are the parameters appearing in the following empirical equations established by Lee and Gurland [4]:

$$H_{wc} = H_{owc} + K_{owc} d^{-\frac{1}{2}} \tag{4}$$

$$H_m = H_{om} + K_{om} l^{-\frac{1}{2}} \tag{5}$$

where

H_{wc} = is the hardness of binderless polycrystalline WC
H_m = the hardness of the binder in WC–Co
d = the mean WC grain size
l = the mean free path in the binder.

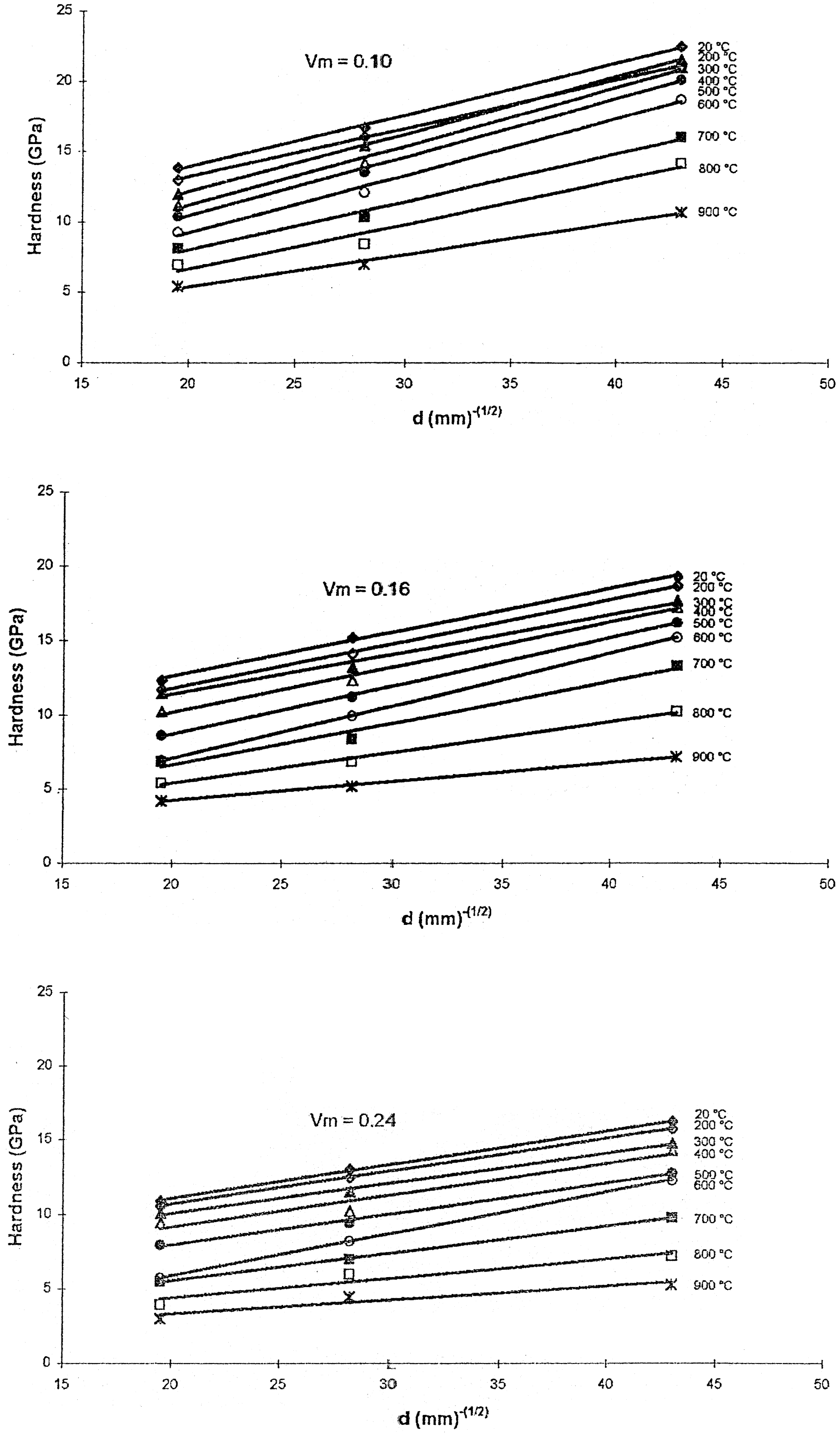

Fig. 3. Plots showing the dependence of hardness on grain size at various temperatures in Hall–Petch coordinates at the three cobalt contents tested V_m = Cobalt volume fraction.

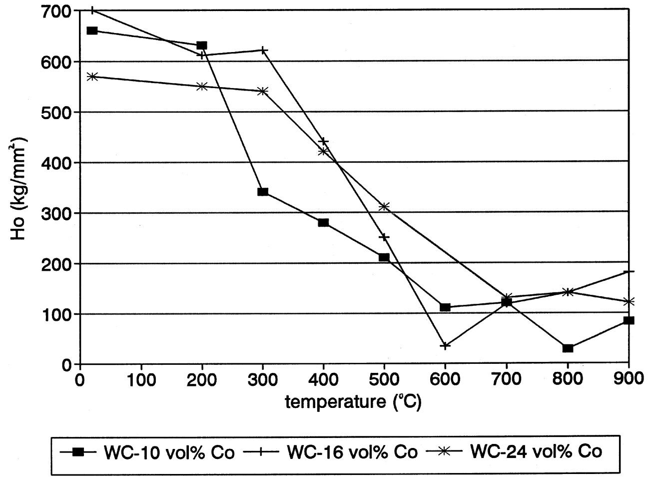

Fig. 4. Plot showing the dependence on temperature and cobalt content of the parameter H_0, defined in the text.

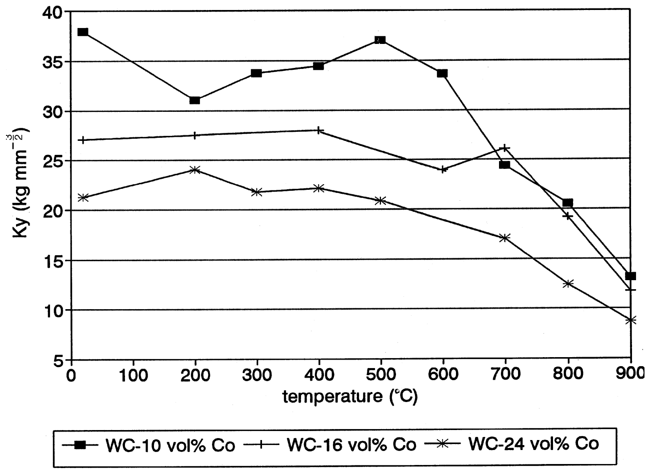

Fig. 5. Plot showing the dependence on temperature and cobalt content of the parameter K_y, defined in the text.

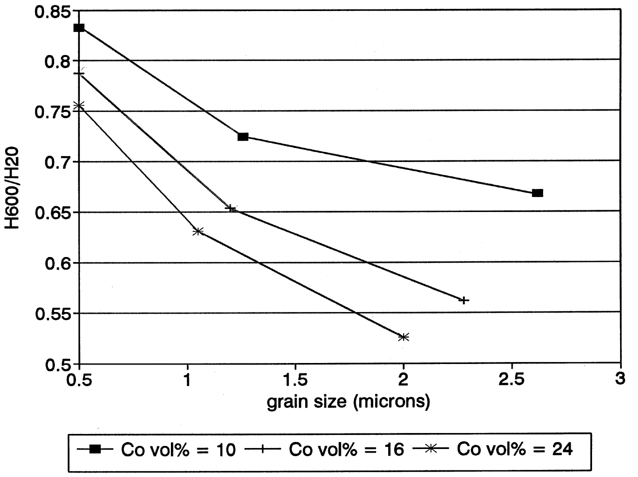

Fig. 6. Plot of the ratio between the hardness of WC–Co at 600°C and the hardness at room temperature versus grain size at three cobalt contents.

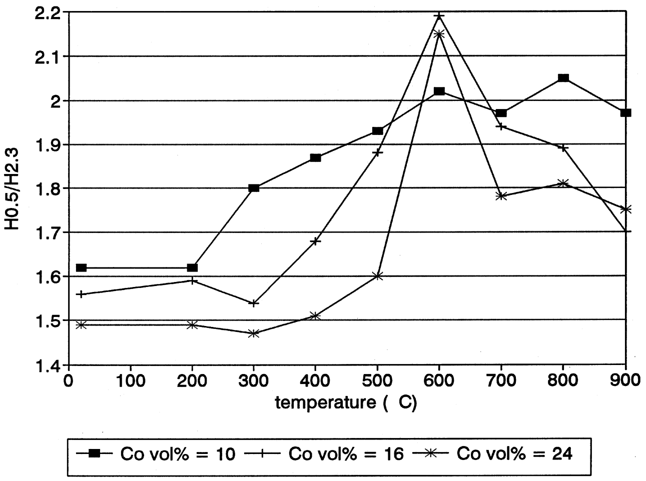

Fig. 7. Plot of the ratio between the hardness of the finest ($d = 0.5$ μm) and the coarsest ($d = 2.3$ μm) grades tested versus temperature at three cobalt contents.

Lee and Gurland [4] determined the values of the constants H_{owc}, K_{owc}, H_{om} and K_{om} at room temperature [4].

Eq. (2) shows that H_0 is related to the intrinsic hardness of the WC and binder phases, H_{owc} and H_{om}, to the carbide volume fraction, V_{wc}, and to the contiguity, C. The hardness of WC single crystals [5] and of cobalt [6] decreases rapidly with increasing temperature only up to about 600°C, which explains the temperature dependence of H_0 (Fig. 4). H_0 is not affected significantly by cobalt content because of the presence of both ($V_{\mathrm{wc}}C$) and ($1 - V_{\mathrm{wc}}C$) in Eq. (2).

Eq. (3) shows that K_y is related to the ease of slip transfer across WC/WC, Co/Co and Co/WC grain boundaries since it is a linear combination of the Hall–Petch parameters K_{owc} and K_{om} of Eqs. (4) and (5). In fact the dependence of K_{y} on temperature (Fig. 5) is similar to the dependence on temperature of the hardness of polycrystalline WC [5], which also softens rapidly only above 500–600°C. K_{y} depends more strongly on cobalt content than H_0 does, on account of the factor $B^{-1/2}$ in Eq. (3).

It is proposed, therefore, that up to approximately 600°C the decrease in the hardness of WC–Co alloys is due mostly to the decrease of the first term in Eq. (1), i.e. the softening of the individual phases (WC and binder), while above 600°C the softening of the alloys is mostly due to easier slip transfer across grain boundaries. An increase in d (Eq. 1)) contributes to the decrease in H. By comparing the curves in Fig. 2 with the curves in Figs. 4 and 5, it appears that the ease of slip transfer across grain boundaries plays the main role in the hardness of WC–Co alloys since, similarly to K_y, the hardness of WC–Co decreases with temperature rapidly only above about 600°C.

The results in Figs. 6 and 7 show respectively that finer grain size alloys and the alloys with lower cobalt content preserve their hardness at high temperature better than the other alloys, and that the advantage of using finer material increases with increasing temperature.

Acknowledgements

The authors wish to thank Professor HE Exner for suggesting important changes to the paper, Vicky Pugsley for the grain size measurements, and IV Gridneva and SI Chugunova for the hardness measurements. The sponsorship of Boart Longyear (Pty) Ltd and the Foundation for Research Development is gratefully acknowledged.

References

[1] Milman YuV, Chugunova S, Goncharuck V, Luyckx S, Northrop IT. Int. J. Refract. Met. & Hard Mater. 1997;15:97.
[2] Gudzov NT, Lozinsky IG, J. Exper. and Theoret. Phys. USSR 1952;22:1249.
[3] Milman YuV, Skljarov OE, Udovenko AP. Works Metrolog. Inst. USSR 1967;N19:167.
[4] Lee HC, Gurland J. Mater. Sci. Eng. 1978;33:25.
[5] Lee M. Met. Trans. A 1983;14A:1625.
[6] Cobalt Monograph. Belgium: Centre d'Information du Cobalt, 1960.