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Low and High Temperature Hardness of WC–6 wt%Co Alloys

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Abstract: This paper reports hardness measurements on WC–6 wt%Co of three different grain sizes in the temperature range from −196 to 900°C. Coarser grades have been found to soften with increasing temperature at a higher rate than finer grades. It has been confirmed that hardness decreases with increasing grain size over the whole range of temperatures and it has been shown that the decrease in hardness with increasing grain size follows a Hall–Petch-type relationship at all the temperatures tested. © 1997 Elsevier Science Limited

1 INTRODUCTION

The data available in the literature on the high temperature hardness of WC–6 wt%Co show that the hardness of this material decreases with increasing temperature and that the hardness of grades with coarser grain size remains lower than the hardness of the grades with finer grain size at all the temperatures investigated, i.e. from 20 to 1000°C.[1–3]

At low temperatures, i.e. below 20°C, no results have been found in the literature on the hardness of WC–6 wt%Co, although some data exist on the low temperature hardness of other hardmetal grades.[4]

The present paper reports the results of the hardness of WC–6 wt%Co in the temperature range from −196 to 900°C and proposes to explain the dependence of hardness on temperature and on WC grain size by means of Lee and Gurland's equation[5] which is known to explain the hardness of hardmetal at room temperature.

2 METHOD

The samples used for this investigation were disks of 14 mm diameter and 3 mm thickness. The microstructures of the three WC–6 wt%Co grades tested are shown in Fig. 1 and the grain size is given in Table 1. The grain size was measured by means of a Leica Q500MC image analyser and the grain size distribution is shown in Fig. 2.

In the temperature range from −196 to 20°C the hardness was measured in an Instron mechanical testing machine with the sample immersed in the cooling liquid.[6] The load on the Vickers indenter was 20 kg. The cooling liquid was a mixture of liquid nitrogen and petroleum ether. The same apparatus and the same load were used to measure the hardness in the temperature range 20–500°C. A radiation furnace was used, in air. In the temperature range 20–900°C measurements were also made at a load of 6 kg, in vacuum, in a BIM-1 installation,[7] where the load on the indenter is determined by the weight of the moving column, weights and indenter. The samples were heated by means of a molybdenum heater.

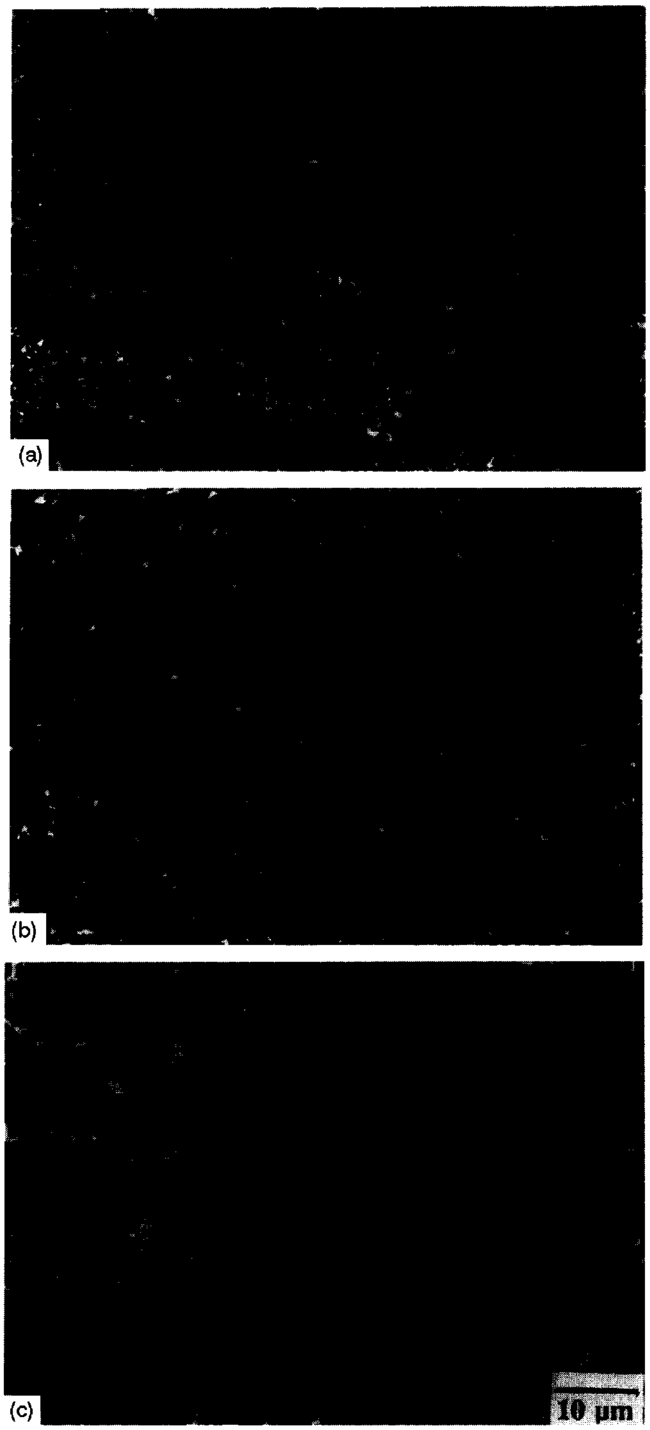

Fig. 1. Microstructure of the three WC–6 wt%Co grades tested: (a) fine grade; (b) medium grade; (c) coarse grade. The three micrographs are at the same magnification.

3 RESULTS

The results of the cold and hot hardness measurements are summarized in Fig. 3. They show that throughout the temperature range the hardness decreases with increasing grain size. They also show that the rate of softening with increasing temperature is high between −196 and 20°C, decreases between 20 and 600°C and increases again above 600°C. The hardness values obtained at indenting loads of 20 and 6 kg are similar, although the former were obtained in air and the latter in vacuum.

Table 2 shows what fraction of the room temperature hardness is left when the temperature is increased above 20°C. It shows that coarser grades soften with increasing temperatures at a higher rate than finer grades.

4 DISCUSSION

The high temperature results in Fig. 3 are in general agreement with the results of other authors.[1–3] The low temperature results cannot be compared with other authors' because none have been found in the literature.

In order to interpret the results in Fig. 3 let us consider the following equation

$$H = H_{wc} V_{wc} \cdot C + H_{m} \cdot (1 - V_{wc} \cdot C) \qquad (1)$$

which was proposed by Lee & Gurland[5] and was found to be in good agreement with hardness results at room temperature.

In equation (1):

H = hardness of WC–Co
H_{wc} = hardness of binderless polycrystalline WC
H_{m} = hardness of the binder phase in WC–Co
C = contiguity of the WC grains
V_{wc} = volume fraction of the WC phase (0·9 in WC–6 wt%Co).

Lee & Gurland found experimentally that H_{wc} and H_{m} follow the Hall–Petch relationships of the type:

Table 1. Results of the grain size measurements on the three WC-6 wt%Co grades tested

WC-6 wt%Co grades	*Mean WC gr size (μm)*	*Std Dev (μm)*	*Nbr of grains measured*
F (Fine)	0·81	0·33	603
M (Medium)	1·58	0·74	395
C (Coarse)	3·55	1·37	473

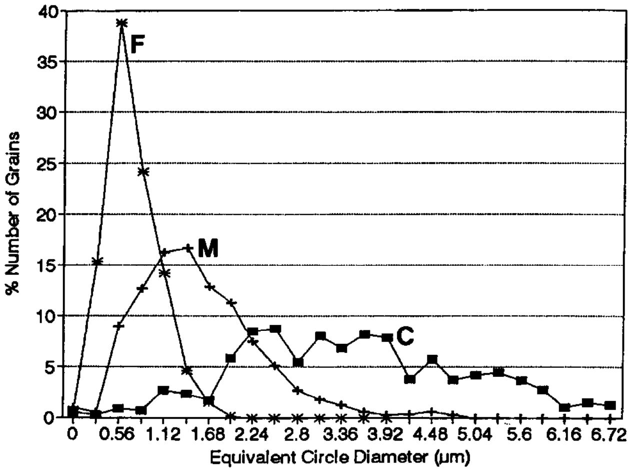

Fig. 2. Grain size distribution of the three WC-6 wt%Co grades tested (see Table 1).

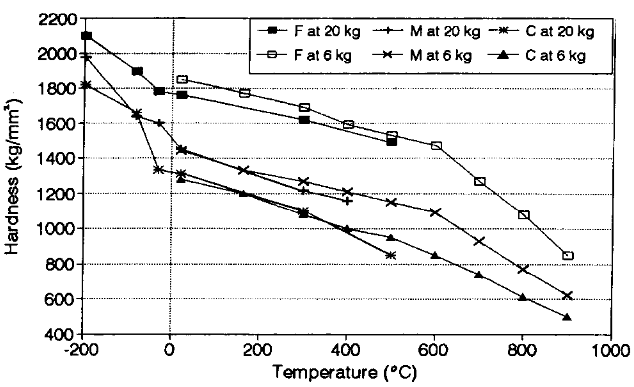

Fig. 3. Results of the hardness measurements at temperatures ranging from −196 to 900°C. As explained in the text, some measurements were done with an indenting load of 20 kg and some with 6 kg.

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

$$H_m=H_{om}+K_{om}\cdot l^{-1/2} \tag{3}$$

where d is the mean WC grain size, l the mean free path in the binder phase, and H_{owc}, K_{owc}, H_{om} and K_{om} are parameters that were determined experimentally.[5] More recently, Sigl & Exner[8] extended Lee & Gurland's measurements and obtained the following results:

$$H_{wc}=1350+21\cdot d^{-1/2} \tag{4}$$

$$H_m=130+16\cdot l^{-1/2} \tag{5}$$

The following relationship exists between d and l:[5]

$$l=\frac{V_m}{(1-V_m)\cdot(1-C)}\cdot d \tag{6}$$

where V_m is the volume fraction of the binder (0·1 in WC-6 wt%Co).

The value of the contiguity, C, varies with cobalt content but does not vary substantially with WC grain size.[5,9] For the grades tested, the contiguity was found by linear analysis to range from 0·55 to 0·65, however by assuming that C is approximately equal to 0·6 for all the grades, the relationship between l and d becomes:

$$l=B\cdot d,\text{ where } B=\frac{V_m}{(1-V_m)\cdot(1-C)}=0{\cdot}28 \tag{7}$$

By substituting (2), (3) and (6) into (1) one obtains:

$$H=H_o+K_y\cdot d^{-1/2} \tag{8}$$

Table 2. Temperatures at which the H/H_{20} ratio is 0·8, 0·7, 0·6 and 0·5 for each of the grades tested. H is the hardness of the grade at the temperature indicated and H_{20} the hardness at room temperature

Grades	*H/H₂₀* 0·8	0·7	0·6	0·5
F	at 580°C	at 700°C	at 775°C	at 875°C
M	at 500°C	at 650°C	at 740°C	at 820°C
C	at 350°C	at 530°C	at 675°C	at 775°C

where:

$$H_o = H_{owc} \cdot V_{wc} \cdot C + H_{om} \cdot (1 - V_{wc} \cdot C) \quad (9)$$

$$K_y = K_{owc} \cdot V_{wc} \cdot C + K_{om} \cdot (1 - V_{wc} \cdot C) \cdot B^{-1/2} \quad (10)$$

Equation (8) suggests that when the cobalt content is constant, a Hall–Petch-type relationship exists between the hardness of WC–Co and the WC grain size.

From the data given above ((4), (5) and (7)) it is possible to calculate the values of the parameters H_o and K_y in (8) at room temperature (since (4) and (5) were obtained at room temperature). These values are:

$$H_o = 789 \text{ kg mm}^{-2} \text{ and } K_y = 25 \text{ kg mm}^{-3/2} \quad (11)$$

In order to verify if (8) is valid above and below room temperature, the hardness values obtained during this investigation were plotted against $d^{-1/2}$, where the values of d are those given in Table 1. Figure 4 shows the results. The correlation coefficients (r) for all the straight lines in Fig. 4 are higher than 0·99 except for the 20 and 165°C lines in Fig. 4(b) (where $r=0{\cdot}98$ and 0·97, respectively) and the −80°C line in Fig. 4(a) (where $r=0{\cdot}86$). Thus the relationships between H and $d^{-1/2}$ can be considered to be linear at all temperatures, the scatter being due to experimental errors and to the wide grain size distribution of the coarse grade.

From the data in Fig. 4 it was possible to derive the parameters H_o and K_y in (8) and plot them against temperature (Fig. 5). Figure 5 shows that at 20°C, H_o and K_y have values very close to those calculated above (see (11)).

Figure 5 shows that H_o decreases monotonically with increasing temperature while K_y increases when the temperature increases from −196 to 20°C, remains approximately constant between 20 and 600°C, and then decreases above 600°C. By adding the H_o and $K_y \cdot d^{-1/2}$ values (using the data in Fig. 5) and plotting the results against temperature, one obtains a curve which has the same behavior as the curves in Fig. 3.

The monotonic decrease of H_o with increasing temperature reflects the decrease of the hardness of both WC and binder with increasing temperature.[1,10] The behavior of K_y reflects the effect of temperature on the resistance to slip transfer across grain boundaries. The constant value of K_y between 20 and 600°C explains the low rate of softening of WC–Co in this temperature interval (Fig. 3).

The higher rate of softening observed in the coarser grades (Table 2) can be explained as follows. The rate of softening can be defined as

$$u = \frac{dH}{H \cdot dT} \quad (12)$$

where T = temperature.

When

$$\frac{dK_y}{dT} \simeq 0$$

(i.e. between 20 and 600°C),

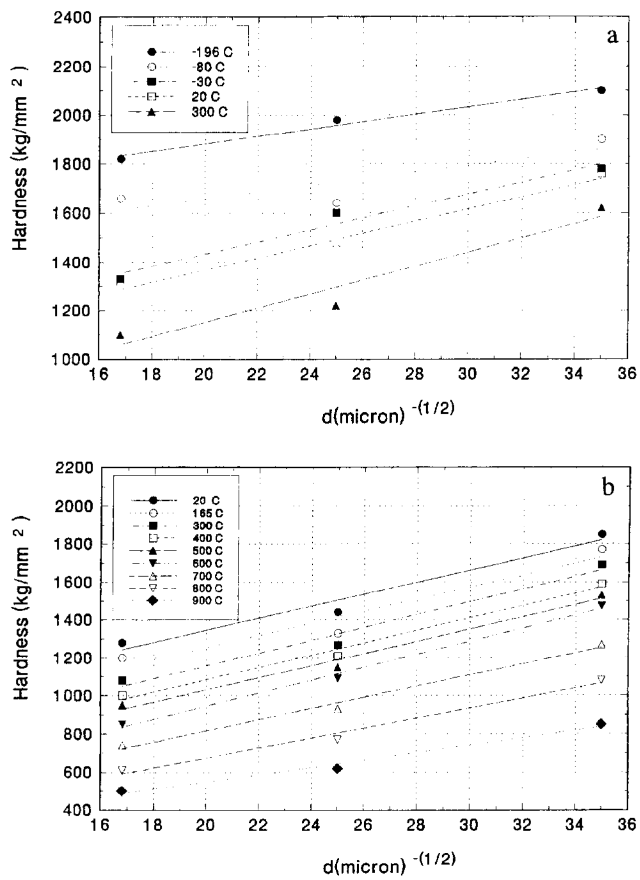

Fig. 4. Plots of the hardness versus $d^{-1/2}$, where d is the mean grain size of the grades tested. Plot (a) summarizes the results obtained at temperatures ranging from −196 to 300°C and at an indenting load of 20 kg. Plot (b) summarizes the results obtained at temperatures ranging from 20 to 900°C and at an indenting load of 6 kg. The correlation coefficients are higher than 0·99 for all the straight lines except for the −80°C line in plot (a) and for the 20 and 165°C lines in plot (b) (see text).

$$u \simeq \frac{\mathrm{d}H_o}{\mathrm{d}T} \cdot \frac{1}{H_o + K_y d^{-1/2}}.$$

Since $\mathrm{d}H_o/\mathrm{d}T$ depends weakly on grain size, when d increases and $d^{-1/2}$ decreases, u increases, consistent with the results in Table 2.

5 CONCLUSIONS

The present investigation has confirmed that the hardness of WC–6 wt%Co decreases with increasing temperature and that thc rate of softening is high between −196 and 20°C, decreases between 20 and 600°C, and increases again above 600°C. In addition, this work has shown that the rate of softening is higher for coarser than for finer grades in the range of temperatures investigated.

By using an equation which was proposed by Lee & Gurland to explain the room temperature hardness of WC–Co, it has been found that at all temperatures the hardness of WC–6 wt%Co decreases with increasing WC grain size according to a Hall–Petch-type relationship.

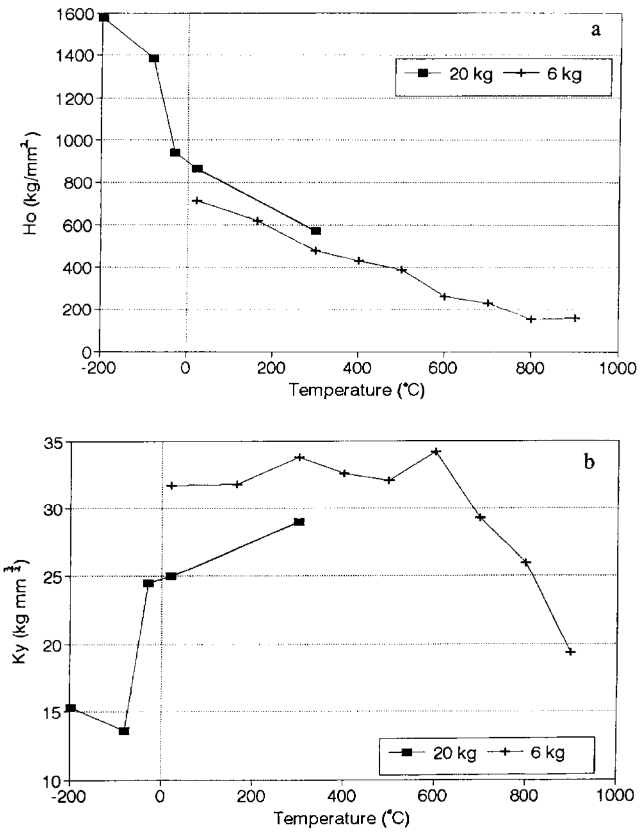

Fig. 5. Plots of the parameters H_o (a) and K_y (b) in (8) versus temperature.

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REFERENCES

1. Lee, M., *Metall. Trans. A* **14A** (1983) 1625.
2. Chatfield, C., *Powder Metall. Int.* **17** (1985) 113.
3. Laugier, M. T., *Mater. Sci. Engng* **A105/106** (1988) 363.
4. Suzuki, H., Tanase, T., Nakayama, F. & Hayashi, K., *J. Japan Soc. Powd. Powd. Metall.* **3** (1978) 32.
5. Lee, H. C. & Gurland, J., *Mater. Sci. Engng* **33** (1978) 125.
6. Milman, Yu. V., Skljarov, O. E. & Udovenko, A. P., Investigations in the branch of hardness measurement, Report Metrological Inst. USSR, N91, 1967, p. 167.
7. Gudzov, N. T. & Lozinsky, I. G., *J. Exp. Theor. Phys. USSR* **22** (1952) 1249.
8. Sigl, L. S. & Exner, H. E., *Mater. Sci. Engng* **A108** (1989) 121.
9. Fischmeister, H., *Proc. Int. Conf. Science of Hard Materials*, Jackson. Plenum Press, New York, p. 14.
10. Betteridge, W., *Cobalt and its Alloys.* Ellis Horwood Ltd Publishers, Chichester, 1982, p. 22.