HARDMETALS
Hardness and Coercivity
Property Maps

Hardmetals based on WC/Co are regularly evaluated by industry and need to be benchmarked for basic mechanical properties such as hardness, wear resistance and toughness. Mechanical properties are determined by the material microstructure and WC grain size is significant in this respect. Magnetic coercivity provides a characterisation tool for indirectly checking the WC grain size. Newer grades of hardmetal often contain materials with a very fine WC grain size and it is important to be able to assess their effects on properties.

Benchmarking can be assisted by the use of “Property Maps”. This Measurement Note evaluates the use of Coercivity and Hardness Property Maps on a range of hardmetals. The materials for investigation were chosen to complement materials previously investigated.

The structural characterisation exercise consisted of the measurement of WC grain size and size distribution. These measurements were then analysed for comparison with model predictions both from hardness and magnetic coercivity measurements. The coercivity data were provided by industry. The measurements were used to construct the Property Maps. These maps allow the effects of differences in structure and properties to be compared and provide a baseline for the evaluation of new materials.

Measurements on materials with a low Co content indicated that the maps were suitable only for specified composition ranges. New models are needed for materials outside these limits, and these should be underpinned by further work investigating the nature of the cobalt distribution.

B Roebuck

March 2002

MATERIALS

Over twenty hardmetals were supplied by industry. The codes and source details are given in Table 1. Some of the materials contained binders with alternatives to Co, for example Ni and Fe/Co/Ni. These materials were classed as the CPM materials, referring to the current DTI programme on characterisation of materials. They were compared with the CAM materials studies in a previous DTI measurement programme [1].

MEASUREMENTS AND RESULTS

Magnetic coercivity measurements were performed at Marshalls Hardmetals Ltd. Magnetic moment data (expressed as $\mu T\ m^3\ kg^{-1}$ of hardmetal) were obtained using the LDJ equipment at NPL. The results of magnetic moment and coercivity measurements are given in Table 1. SEM and optical micrographs of the materials were obtained at magnifications of $\times 1k - \times 20\,k$. Grain size measurements were made at NPL using the linear intercept method of at least 200 intercepts from scanning electron micrographs. The results of the grain size measurements are given in Table 2. The results were compared with data from a previous DTI project, Characterisation of Advanced Materials (CAM) [1].

DISCUSSION AND PROPERTY MAPS

Two kinds of property map were considered.

In the first type the property of interest is plotted against a microstructural feature that affects that property. In this case the microstructural feature was the WC grain size, d. It is recognised that other parameters are important, such as the content and composition of the cobalt binder phase or the size distribution of WC grains. For this note the property maps were developed assuming a composition approximately in the centre of the two-phase WC/Co region and a conventional WC grain size distribution with the arithmetic number mean intercept, *d*, as the parameter characterising WC grain size. Thus Coercivity and Hardness were mapped against WC grain size.

In the second type of map, two properties were compared with each other, i.e. Coercivity was compared with Hardness.

MAGNETIC PROPERTY MAP

Grain size is usually related to coercivity using an inverse expression [2].

$$K = a + bd^{-1} \qquad (1)$$

where *a* and *b* are constants, *K* is the coercivity in kA m^{-1} and *d* is the WC arithmetic mean linear intercept in µm. Preliminary work found that, because the variation of *a* and *b* with Co content was reasonably linear, further analysis allowed an expression to be written for the variation of coercivity, *K*, with grain size, *d* for 6 < Co < 25 wt% as follows:

$$K = (c_1 + d_1 * \text{wt\%Co}) + (c_2 + d_2 * \text{wt\%Co}) * (1/d) \qquad (2)$$

where $c_1 = 1.44$ $d_1 = 0.04$
$c_2 = 12.47$ $d_2 = -0.37$

with *K* in kA m^{-1} and *d* in µm. This expression can be used to generate a *K vs.* 1/*d* property map. This is shown in Fig 1 with the new measurements from the CPM materials superimposed. It can be seen that there is good agreement for the materials with greater than 6% Co binder-phase, and thus the expressions used to generate the property map have been validated by the current work. However, the two hardmetals (coded cw3 and shm3) with a 3% binder phase and a fine-grained matrix did not fit the map. Therefore, it must be concluded that further work is needed on a greater spread of materials to examine the coercivity/grain size relation for materials outside the range covered by the present data set, especially for binder contents less than 6 wt% Co. The reason for the non-compliance of the low Co, fine-grained materials, must lie in the nature of the distribution of the Co-phase. New work is needed to investigate the form of the Co distribution in these materials.

TABLE 1 - Material Properties

Material Code	Source	Nominal binder content (Co, wt%)	Magnetic coercivity		Magnetic moment $\mu T\ m^3\ kg^{-1}$
			Marshalls		NPL
			Oersteds	kA m^{-1}	
cw3	CW Carbides	3	353	28.1	0.42-0.45
cwn8	CW Carbides	8^{+}	0	0	0.2
cwfnc20	CW Carbides	20^{++}			2.93
ma6	Marshalls	6	158	12.6	0.87
ma11	Marshalls	11	49	3.9	1.64
ma14	Marshalls	14	112	8.9	1.98
macn9	Marshalls	9^{+}	367	29.2	0.83-0.95
n15	Neepsend	15	185	14.7	1.8-2.0
t25	Teco	25	85	6.8	2.82
h10	Hoybide	10	229	18.2	1.49
shm3	Sandvik HM	3.3	402	32.0	0.45
shmcn5	Sandvik HM	5.3^{+}	345	27.4	0.45
shm9	Sandvik HM	9*	491	39.1	1.13
d10	Dymet	10	123	9.8	1.35
uc9	Hydra	9	51	4.1	1.35
t	Hydra	9	106	8.4	1.1
b9	Boart	9	145	11.6	1.15-1.18
x160	Kennametal	10	232	18.5	1.26
k322	Kennametal	9.75	181	14.4	1.26
k801	Kennametal	6^{+}	53.9	4.3	0.18
k3520	Kennametal	20	64.1	5.1	2.88

* round testpieces, 3.25 mm diameter $^{+}$ Ni or Co-Ni alloy $^{++}$ Fe, Ni, Co alloy

TABLE 2 - Additional Properties

Material code	HV30	Arithmetic mean linear intercept, μm	Density Mg m^{-3}
macn9	1683	0.23	14.33
shm3	2071	0.31	15.32
shmcn5	1953	0.37	15.01
cw3	1918	0.4	15.26
h10	1367	0.41	14.41
n15	1248	0.49	14.11
x160	1626	0.64	14.41
k322	1451	0.71	14.58
t25	980	0.77	13.28
b9	1438	0.82	14.72
cwn8	1301	0.85	14.73
ma14	1206	0.91	14.20
ma6	1518	1.03	14.91
d10	1336	1.05	14.54
t	1344	1.68	14.48
k3520	883	2.30	13.50
k801	1063	2.70	14.92
uc9	996	4.97	14.52
ma11	955	5.16	14.35

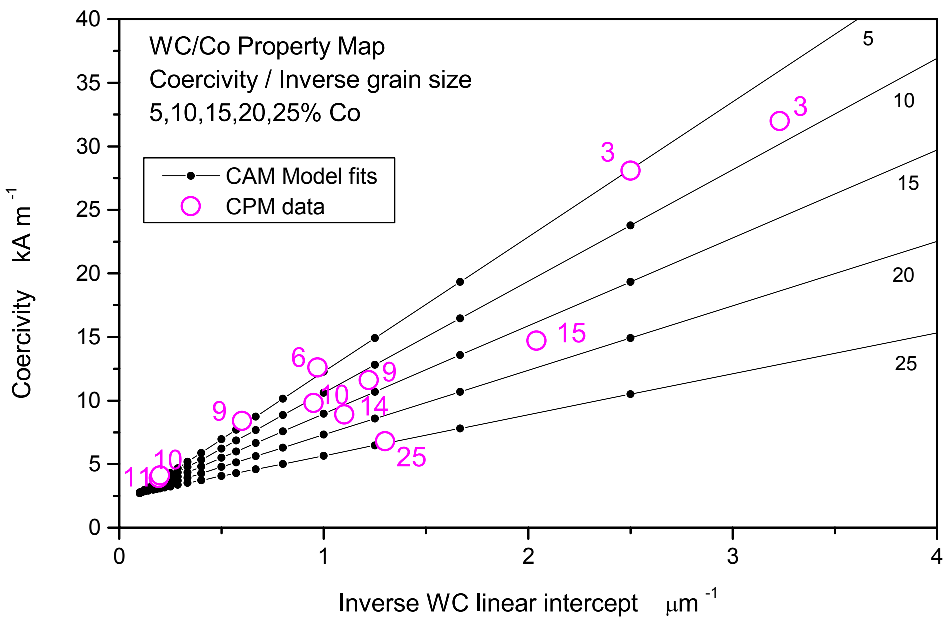

Fig 1 Coercivity/WC Intercept property map overlaid with CPM data.

Measurements from the new sets of CPM materials were added to the data used to generate expression (2). The combined data was used to generate expressions for the 6% and 10% Co hardmetals for a wider range of *K* (up to 35 kA m^{-1} rather than 15 kA m^{-1} above). The results are shown in Fig 2 and are given here as:

$$6\%\ \text{Co}: \quad K = 3.94 + 8.79\ d^{-1}\ \text{for}\ K < 35\ \text{kA m}^{-1} \quad (3)$$

$$10\%\ \text{Co}: \quad K = 3.34 + 7.08\ d^{-1}\ \text{for}\ K < 35\ \text{kA m}^{-1} \quad (4)$$

It is also possible that microstructural instabilities in low C hardmetals or residual stresses could affect measurements of coercivity through changes in internal strain and composition. These effects could contribute added uncertainty to the correlation between grain size and coercivity and should be examined in more detail.

HARDNESS MAP

Hardness is usually related to grain size through the Hall-Petch equation [1]

$$H = e + f d^{-0.5} \quad (5)$$

where e and f are constants, H is the hardness and d is the arithmetic mean linear intercept grain size. Previous work [1] had obtained the following values for the dependency of e and f on Co content

$$e = 888 - 9.9\ W_{Co} \quad (6)$$
$$f = 229 + 532/(\exp[(W_{Co}-6)/6.7]) \quad (7)$$

The resulting microstructural property map is shown in Fig 3 with the CPM data super-imposed on the graph. As for the coercivity map it can be seen that the hardness results for the CPM materials comply reasonably well with the preliminary maps except for the 3% Co materials. These materials had fine grain sizes and there may also be a deviation from Hall-Petch behaviour as grain size decreases. Where there are deviations it is possible to explain the differences in terms of the microstructure, for example:

h10 – high graphite content, therefore softer
macn9 – fine grain size, deviation from Hall-Petch?
k801 – very wide grain size, therefore much softer
cwn8 – fairly wide grain size, therefore softer
x160 – very uniform structure, slightly harder.

Altogether in the CAM and CPM programmes, over 130 hardmetals have now been characterised. All this data is plotted in Fig 4. Two mapping approaches have been compared for the coefficient *f*. In the first case a linear expression is used with

$$f = 654 - 497\ V_{Co} \quad (8)$$

In the second case

$$f = 310 + 289/(\exp[(V_{Co} - 0.13)/0.16] \quad (9)$$

where V_{Co} is the volume fraction Co, as opposed to weight fraction, W_{Co}, used above.

For both approaches

$$e = 1178 - 1326\ V_{Co} \quad (10)$$

In either case the maps fit the data reasonably well and it is recommended that the linear form for f is used as the exponential form results in large errors for low values of V_{Co}.

COMPARATIVE PROPERTY MAP

The expressions developed above for the Microstructure/Property maps were used to derive a comparative property map between K and Hardness (*H*). The results of measurements in the CPM set of materials are shown in Fig 5 confirming the validity of the maps previously derived with the range 6-30% Co and intermediate WC grain sizes. However, as for the coercivity/intercept maps, it can be seen that the 3% Co and fine grained materials did not conform to the general trends where differences were observed, micro-structure observations were used to explain the variance. For example:
h10 – high graphite content, lower than model fit
k801 – very wide grain size, higher coercivity than model
x160 – uniform grain size, lower coercivity than model
cwn8 – Ni bonded, zero coercivity.

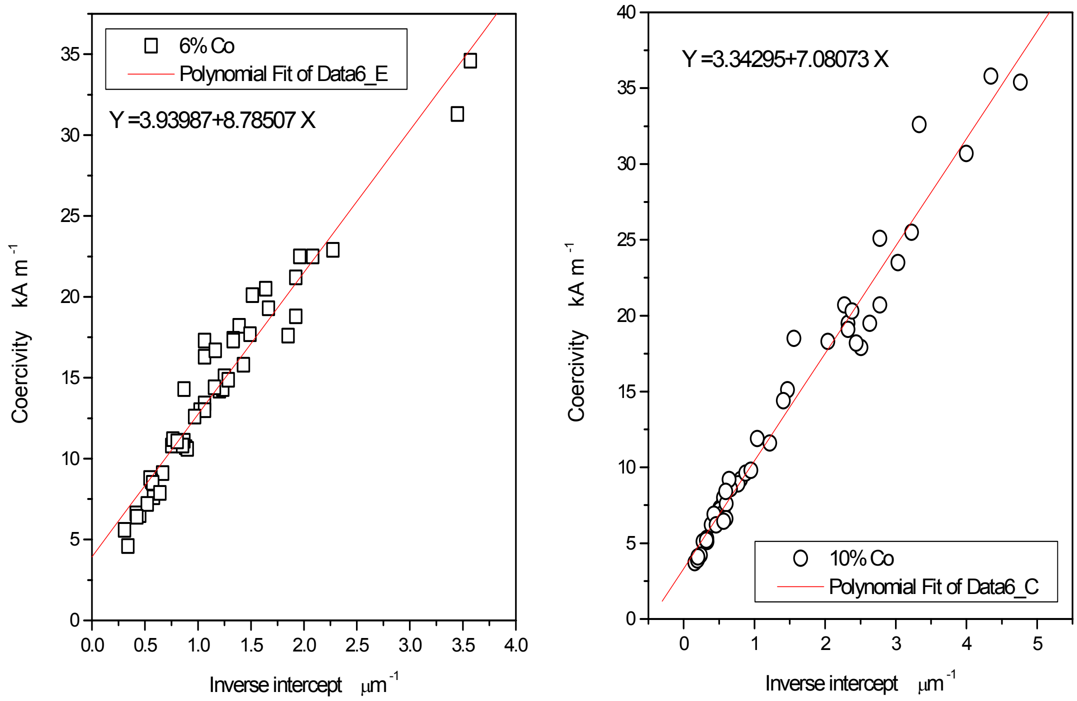

Fig 2 Coercivity (K)/WC intercept size linear fit for $K < 35$ kA/m for 6% and 10% Co hardmetals.

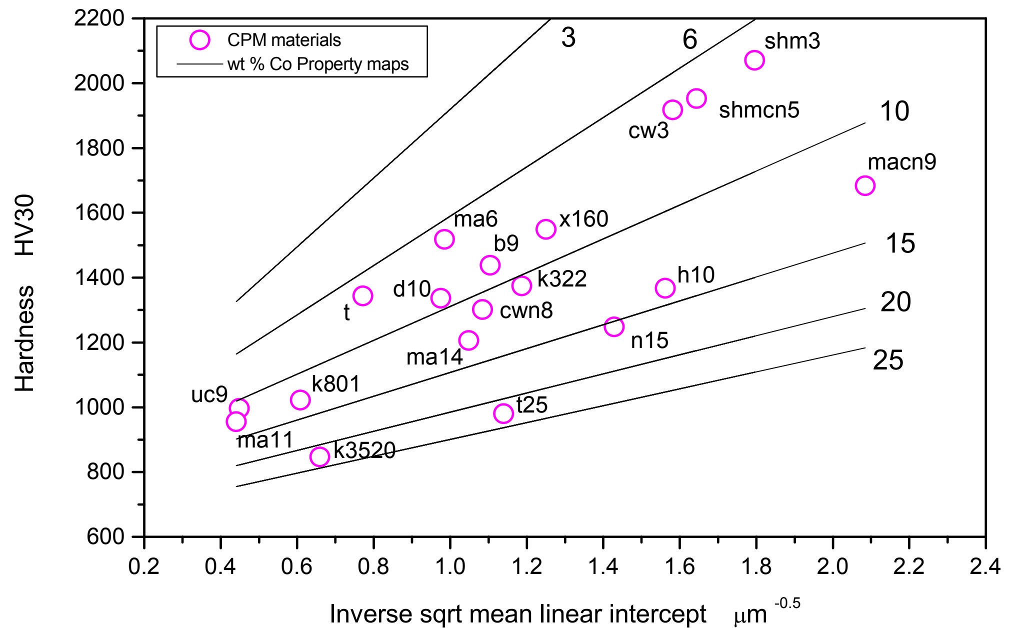

Fig 3 Hardness/WC intercept property map overlaid with CPM results.

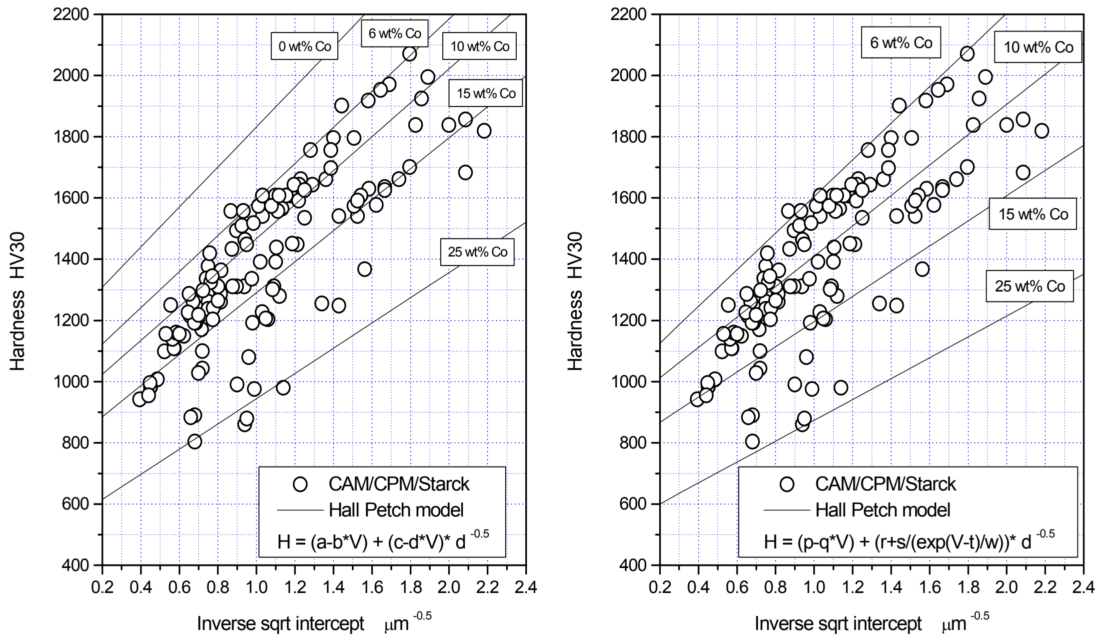

Fig 4 Hardness/WC intercept property map for all data.

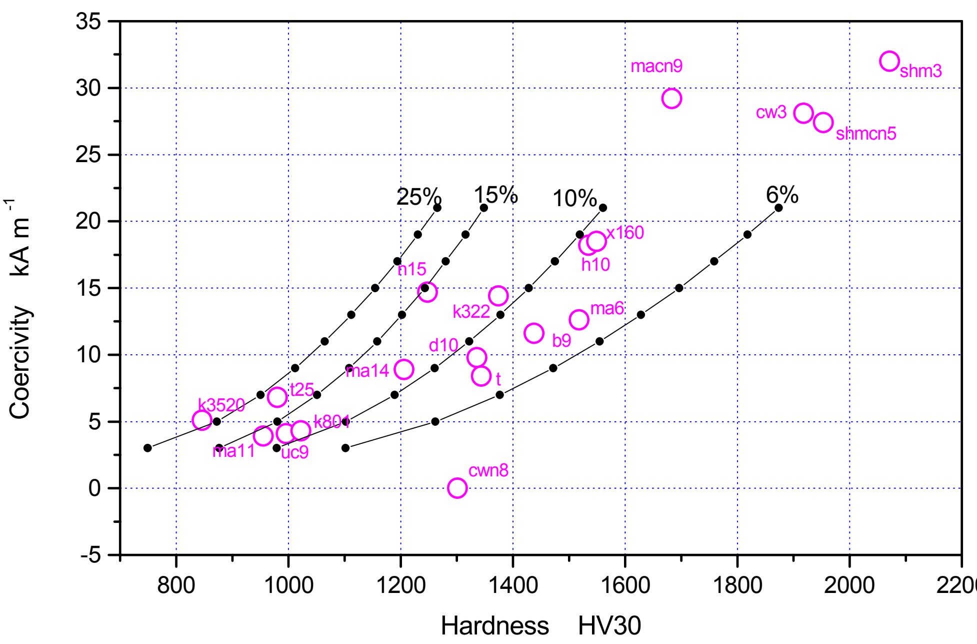

Fig 5 Coercivity/Hardness Property Map.

SUMMARY

Over 20 hardmetals were characterised for their coercivity and hardness. The results of the measurements combined with data from previous work form an extended baseline data set that has been used to evaluate the expressions underlying various Property Maps.

The results of the tests were used to extend three Property Maps, two based on microstructure and one based on a property comparison. These comprised:

WC Grain Size - Microstructure: Coercivity/WC grain size	WC Grain Size - Microstructure Hardness/WC grain size

Comparative Map
Coercivity/Hardness

Further maps are possible and can be derived using the expressions that were developed to map property against microstructural parameters.

REFERENCES

1. B Roebuck, M G Gee, E G Bennett and W P Byrne. Characterisation of Baseline Hardmetals Using Property Maps, NPL Report CMMT(A)172, April 1999.

2. B Roebuck. Terminology, Testing, Properties, Imaging and Models for Fine Grained Hardmetals. Int J. Refractory Metals and Hard Materials, 13, 1995, 265-279.

ACKNOWLEDGEMENTS

The work reported in this document was performed as part of the MTS Programme on Characterisation for the Performance of Materials, a programme of underpinning research financed by the UK Department of Trade and Industry. Members of the British Hardmetal Association Research Group are thanked for the supply of materials and the results of in-house characterisation tests and comments on the development of property maps.

FOR FURTHER INFORMATION CONTACT

Dr B Roebuck
Materials Centre
National Physical Laboratory
Queens Road
Teddington, Middlesex TW11 0LW

Tel: 020 8943 6298
Fax: 020 8943 2989
e-mail: bryan.roebuck@npl.co.uk