

An Interlaboratory Exercise on the Magnetic Properties of Various WC Hardmetals

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ABSTRACT

An interlaboratory comparison exercise has been conducted to investigate the reproducibility of coercivity and magnetic moment/saturation measurements on a range of WC based hardmetals.

The measurements were made at seven collaborating organisations, six of which were industrial companies, and analysed at NPL. Seven materials were evaluated with a range of WC grain sizes from 0.3-3 μm and cobalt contents from 3-15 wt%.

It was found that the standard deviation of the magnetic coercivity value was dependent on WC grain size, with a higher uncertainty associated with the higher values of coercivity (smaller grain size). In contrast there was no clear dependence of the uncertainty in magnetic moment on structure, except for the materials with the very lowest values and they had a larger standard deviation.

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ISSN 1473 2734

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by Dr C Lea, Head, NPL Materials Centre

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1 INTRODUCTION

Hardmetal products which have consistent properties are vital to many sectors of engineering industry. The use of non-destructive methods to assess consistency of structure is very important because hardmetals have microstructures on a very fine scale which are difficult to inspect and they are strong and not easy to test mechanically. However, hardmetals contain cobalt which is ferromagnetic. Consequently measurements of magnetic properties are widely used in the industry to assess consistency. Both coercive force and magnetic moments are measured for this purpose. New hardmetals based on WC need to be compared with conventional materials for basic properties such as hardness, wear resistance and toughness. Magnetic coercivity provides the characterisation tool for indirectly checking the WC grain size. As the grain size decreases the coercivity increases [1]. Magnetic moment/saturation provides a measure of the composition of the cobalt binder phase, through indicating the solute W content. As the W content increases the magnetic moment/saturation decreases.

1.1 MAGNETIC MOMEN

There are a number of different ways of expressing the results of magnetic moment values which can lead to some confusion. Also, there is no standard equipment for the purpose. Often companies use in-house equipment that can often lead to misunderstandings in interpretation of results because the cobalt phase can differ in its composition. Previous work [2] has discussed the background to the correct use of units and the different methods for expressing the results on typical hardmetals. The main points are summarised in this introduction.

Tungsten carbide/cobalt hardmetals generally contain 5-20 wt% cobalt as a binder-phase. The cobalt binder-phase contains both tungsten and carbon in solution. The amount of tungsten dissolved in the cobalt binder-phase can be assessed by measurement of the magnetic saturation or magnetic moment of the hardmetal because the saturation value of cobalt decreases linearly with the addition of tungsten and is not affected by the amount of carbon in solution. The term 'magnetic saturation' is an abbreviation for the saturation (or maximum) value of magnetic induction that can be obtained in a testpiece in a strong magnetic field.

Definitions

$4\pi I_s$, J_s	saturation induction (polarisation), tesla
I_s	magnetic moment/unit volume (intensity of magnetisation/unit volume)
	magnetic moment/unit weight (intensity of magnetisation/unit wt)
	I/ρ where ρ is the density.

Units

Magnetic moment	Wb m
magnetic moment/unit volume	Wb m ⁻² (T, tesla)
magnetic moment/unit mass	Wb m kg ⁻¹ or T m ³ kg ⁻¹

Table 1 - Units

Description	Non-SI metric	SI
$4\pi I_s$, J_s Saturation induction (polarisation)	gauss	tesla
$4\pi\sigma$ Magnetic saturation/unit wt	gauss $\text{cm}^3 \text{g}^{-1}$	tesla $\text{m}^3 \text{kg}^{-1}$
σ Magnetic moment/unit wt	gauss $\text{cm}^3 \text{g}^{-1}$	tesla $\text{m}^3 \text{kg}^{-1}$

$$1 \text{ tesla} = 10^4 \text{ gauss}$$

$$1 \text{ gauss cm}^3 \text{g}^{-1} = 0.1 \mu\text{T m}^3 \text{kg}^{-1}$$

Physical properties of pure cobalt

Density, ρ	8850 kg m^{-3}
saturation induction/unit volume, $4\pi I_{\text{Co}}$	17870 gauss = 1.787 tesla
saturation induction (magnetic saturation)/ unit wt, $4\pi\sigma_{\text{Co}}$	201.9 $\mu\text{T m}^3 \text{kg}^{-1}$
magnetic moment/unit wt, σ_{Co}	16.1 $\mu\text{T m}^3 \text{kg}^{-1}$

It is clear that confusion can arise between the saturation or moment values that can be quoted for hardmetals. For example, several methods are used that include:

- reference to the magnetic saturation or moment value of the hardmetal
- reference to the magnetic saturation or moment value of the Co binder-phase (Co-W-C) in the hardmetal.

NB magnetic moment is converted to magnetic saturation by 4π multiplication.

Saturation values are sometimes expressed as a percentage of the maximum expected for a nominally pure Co binder phase.

The different methods are given in Tables 2 and 3 for 5, 10 and 15 wt% Co hardmetals.

Table 2 - Illustrative table of magnetic saturation and moment per unit wt of hardmetal or binder-phase. SI units - $\mu\text{T m}^3 \text{kg}^{-1}$

	5 wt% Co*	10wt% Co*	15 wt% Co*
<i>Hardmetal</i>			
Magnetic saturation, $4\pi\sigma$	10.1	20.2	30.3
Magnetic moment, σ	0.80	1.61	2.41
<i>Binder-phase</i>			
Magnetic saturation, $4\pi\sigma$	202	202	202
Magnetic moment, σ	16.1	16.1	16.1

* Binder assumed to be pure Co.

Table 3 - Typical ranges of magnetic saturation and moment values. SI units – $\mu\text{T m}^3 \text{ kg}^{-1}$

	5 wt% Co	10wt% Co	15 wt% Co
<i>Hardmetal</i>			
Magnetic saturation, $4\pi\sigma$	8.0-10.1	16.1-20.2	24.1-30.3
Magnetic moment, σ	0.64-0.80	1.28-1.61	1.92-2.41
Percentage saturation	80-100	80-100	80-100
<i>Binder-phase</i>			
Magnetic saturation, $4\pi\sigma$	160-202	160-202	160-202
Magnetic moment, σ	12.8-16.1	12.8-16.1	12.8-16.1
Percentage saturation	80-100	80-100	80-100

.2 MAGNETIC COERCIVITY

Grain size is usually related to coercivity using an inverse expression [1]

$$K = a + b d^{-1} \quad (1)$$

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 . It is important therefore to understand what uncertainty there is in the measurement of K in order to underpin the confidence attributed to a calculated value of grain size, d . Coercivity is often expressed in Oersteds as well as kA m^{-1} . The conversion factor is 12.57 (4π) i.e. the oersted value is converted to kA m^{-1} by dividing by 12.57.

There is some concern that the uncertainty associated with the magnetic measurements increases as the WC grain size decreases. Consequently an interlaboratory exercise has been conducted, involving six hardmetal companies, on a range of hardmetals with sub-micrometre sized WC grains. Some of the materials contained alloy binder phases, with the Co being partly substituted by Ni.

2 MATERIALS AND MEASUREMENTS

The materials selected for the exercise were obtained from a wider group of twenty hardmetals that had been supplied by industry. These materials were classed as the CPM materials, referring to the current DTI programme on characterisation of materials. The codes and source details are given in Table 4. Some of the materials contained binders with alternatives to Co, for example Co-Ni alloys. The materials were chosen to represent high and medium values of coercivity, i.e. greater than 15 kA m^{-1} .

Table 4 - Properties

Material Code	Source	Binder content **	Magnetic ⁺ coercivity		Magnetic ⁺ moment	Hardness (NPL)	Grain size, arithmetic mean linear intercept,	Density (NPL)
		wt%	Oersteds	kA m ⁻¹	$\mu\text{T m}^3 \text{ kg}^{-1}$	HV30	μm	Mg m ⁻³
cw3	CW Carbides	3	353	28.1	0.42-0.45	1918	0.4	15.26
macn9	Marshalls	9 ⁺⁺	367	29.2	0.83-0.95	1683	0.23	14.43
n15	Neepsend	14.5	185	14.7	1.8-2.0	1248	0.49	14.11
shm3	Sandvik HM	3.3	402	32.0	0.45	2071	0.31	15.32
shmcn5	Sandvik HM	5 ⁺⁺⁺	345	27.4	0.45	1953	0.37	15.01
shm9	Sandvik HM	9	491	39.1	1.13	2000	-	-
x160	Kennametal	10	232	18.5	1.26	1626	0.64	14.41

⁺ Measured at Marshalls Hard Metals⁺⁺ Co-Ni alloy (6% Co, 3% Ni)^{*} Measured at NPL using LDJ instrument⁺⁺⁺ Co-Ni alloy (3.3% Co, 1.1% Ni, 0.5% Cr)^{**} Analysed at Sandvik Hard Materials (HM)

Two groups of sample dimensions were selected for the tests. One group had the dimensions 2 × 5 × 40 mm (coded batch B, for bend testpiece) and the other group had dimensions 40 × 20 × 5 mm (coded batch W, for wear testpiece); except for sample shm9, which was in the form of 3 mm diameter rod, about 5 mm long. This was classed as type B for comparison purposes. Seven organisations took part in the exercise (see Table 5). One of the organisations did not obtain coercivity data (Org 6) and one did not make measurements of magnetic moment (Org 4). The type of equipment used is given in Table 2.

Table 5 – Participating Organisations

	Equipment			Equipment	
	Coercivity ⁺	Magnetic Moment		Coercivity ⁺	Magnetic Moment
Marshalls Hard Metals	FC 1.095	Setaram Sigmameter D6025	Boart Longyear	FC-CS 1.096	Setaram (1.0T)
C W Carbides	FC 1.093	-	Sandvik Hard Materials	FC 1.096	Setaram (99.8%-pure Co)
Hoybide	FC 1.095	Magnatech	NPL	-	LDJ (0.75T)
Teco	L15T Coercimeter KM-1	Magnatech			

FC Coerster Coercimat

3 RESULTS AND DISCUSSION

The results for each organisation are given in Appendix A. The organisations are numbered 1-7 to retain anonymity. In some cases individual measurement values were supplied, from which a mean value was calculated. In other cases only the mean value was supplied. For these measurements an average had been taken of two repeat determinations.

3. COERCIVITY

The coercivity values are given in both oersteds and the SI unit, kA m^{-1} . The coercivity data from all the participating organisations are shown in Fig 1 for comparison. It can be seen that four of the organisations returned values that agreed quite closely but two organisations were significantly different, especially for the long rectangular beams (sample B). These results were therefore excluded in an analysis of uncertainty.

The data are plotted in sequence equivalent to that in the tables in Appendix A, with the smaller samples (type B) plotted on the left hand side of the graph and the larger samples (type W) on the right hand side of graph. Note that there is only one set of results for material shm9.

The standard deviation and coefficient of variation of the mean values was calculated (Table 6) and the results are plotted in Fig 2.

Table 6 Coercivity – Coefficient of Variation

	Mean value	Coefficient of variation %	Sample type
cw3	27.2	2.6	B
macn9	28.3	1.7	B
n15	13.1	1.0	B
x160	18.0	1.2	B
shm3	31.6	3.6	B
shmcn5	26.5	1.5	B
shm9	38.5	5.5	B*
cw3	29.6	2.7	W
macn9	28.4	0.9	W
n15	18.1	1.0	W
x160	13.6	1.7	W
shm3	31.9	2.6	W
shmcn5	27.3	0.8	W

* 3 mm diameter rod (shm9)

It can be seen that there is an increasing trend of coefficient of variation with increasing value of coercivity and that this trend is more marked in the smaller testpieces.

An alternative method of presentation of the results is shown in Fig 3 where the values of coercivity for each organisation for four of the materials are normalised with respect to the overall mean and ranked in value. It can be seen that there is a wider distribution of values for the two materials shm3 and shm9 in comparison with samples n15 and x160. Materials shm3 and shm9 had finer WC grain sizes and higher coercivities than n15 and x160.

3.2 MAGNETIC MOMENT

The magnetic moment/saturation values were returned using several different methods as described in the introduction. These are summarised in Table 7.

Table 7 Magnetic Moment (Saturation) Values

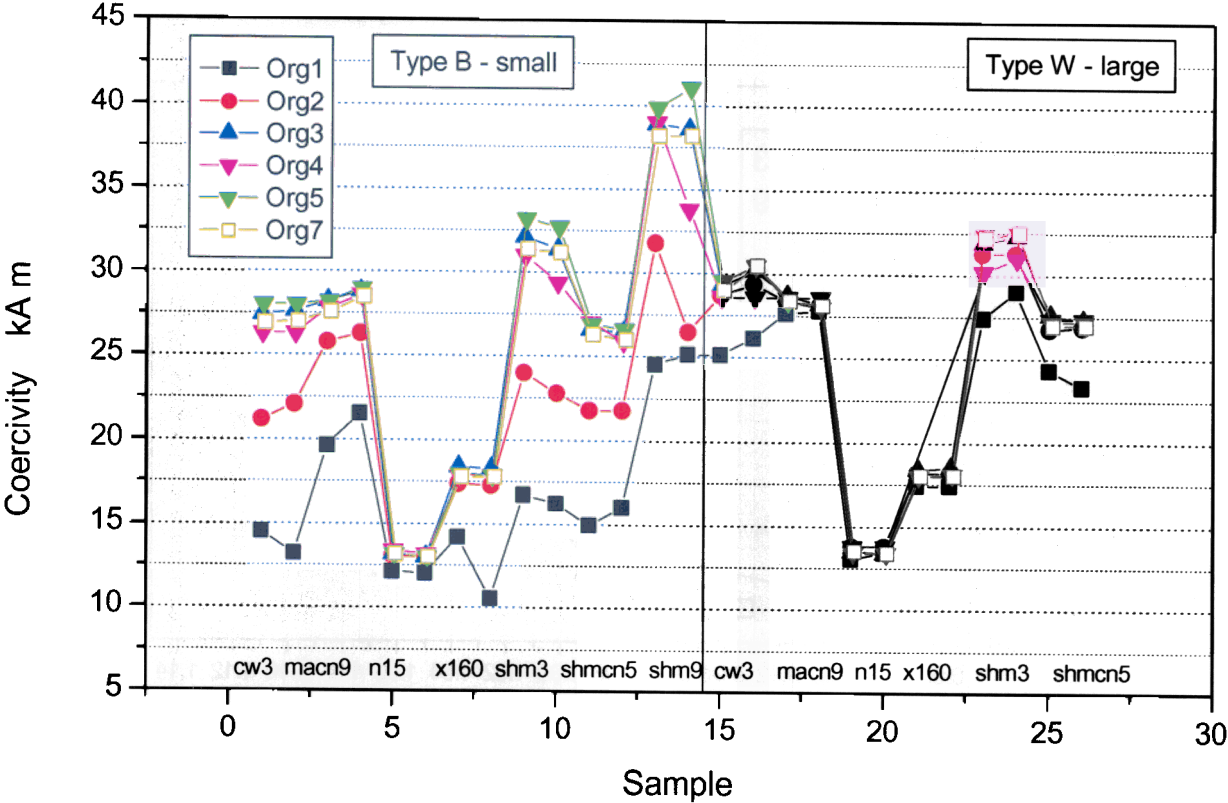
Organisation	Method
1	Expressed as % Co
2	Expressed as % Co
3	Related to the value for pure Co of 161 gauss.cm ³ g ⁻¹ (16.1 $\mu\text{T m}^3 \text{ kg}^{-1}$)
5	Expressed as magnetic saturation, $4\pi\sigma$, where σ is magnetic moment
6	Magnetic moment, $\mu\text{T m}^3 \text{ kg}^{-1}$
7	Expressed as % Co

All the data were converted to magnetic moment / unit wt of hardmetal values, σ ($\mu\text{T m}^3 \text{ kg}^{-1}$), for comparison. Also given in the tables in the Appendix is a column of normalised moment values (normalised with reference to sample WCP/4/15-n15, size B), again for comparative purposes.

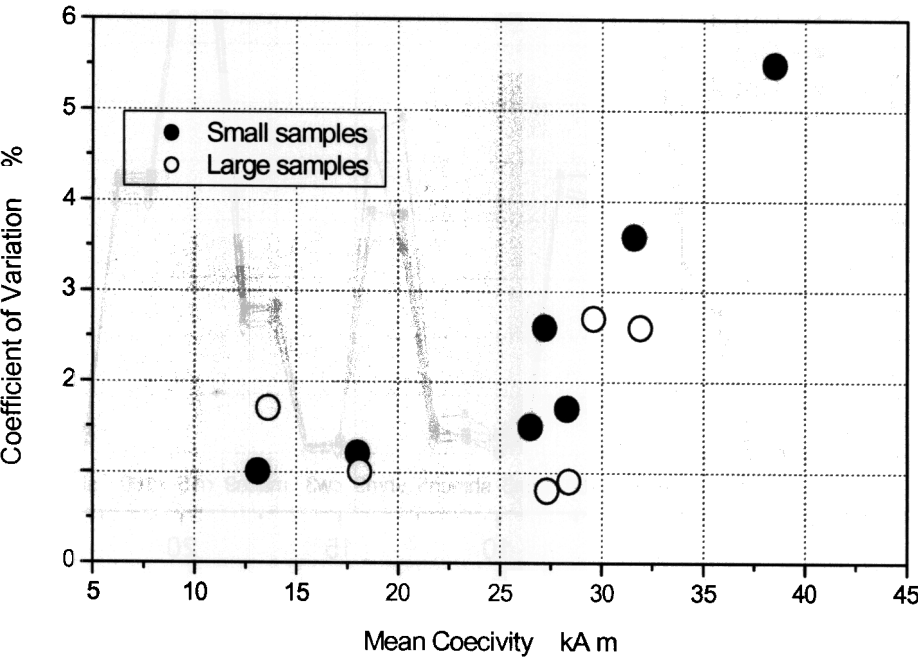
The magnetic moment data from all the participating organisations are shown in Fig 4 for comparison. The data are plotted in sequence to that equivalent in the tables in Appendix A. The standard deviation and coefficient of variation of the mean values was calculated (Table 8) and the results are plotted in Figs 5 and 6 against sample and magnetic moment respectively excluding the obvious outlier points from Org 6 and Org 2 for sample shm9. There is no clear dependence of coefficient of variation on moment value, except that for materials with the lowest value (approximately $0.45 \mu\text{T m}^3 \text{ kg}^{-1}$) there was a larger variation in coefficient of variation. Sample shm9 also had some outlier values, possibly because of the very small size of the samples.

Table 8

Material	All data		Excluding shm9 outlier	
	Mean value $\mu\text{T m}^3 \text{ kg}^{-1}$	Coefficient of variation %	Mean value $\mu\text{T m}^3 \text{ kg}^{-1}$	Coefficient of variation %
cw3	0.46	4.28	0.46	4.28
macn9	0.93	8.21	0.93	8.21
n15	2.13	2.26	2.13	2.26
x160	1.31	2.83	1.31	2.83
shm3	0.46	6.43	0.46	6.43
shmcn5	0.48	6.16	0.48	6.16
shm9	1.26	12.11	1.18	4.17
cw3	0.42	3.57	0.42	3.57
macn9	0.87	3.31	0.87	3.31
n15	2.11	4.08	2.11	4.08
x160	1.31	3.15	1.31	3.15
shm3	0.46	4.76	0.46	4.76
shmcn5	0.48	7.2	0.48	7.2



Comparative plot of coercivity data.



Coefficient of variation of coercivity measurements.

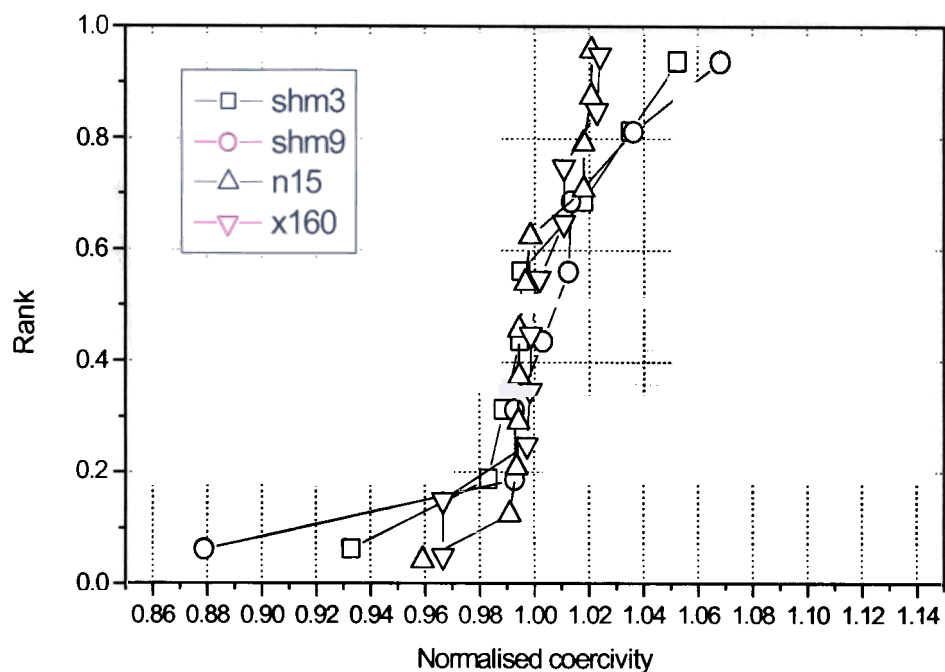


Fig 3 Ranked plot of coercivity values for samples shm3, shm9, n15 and x160.

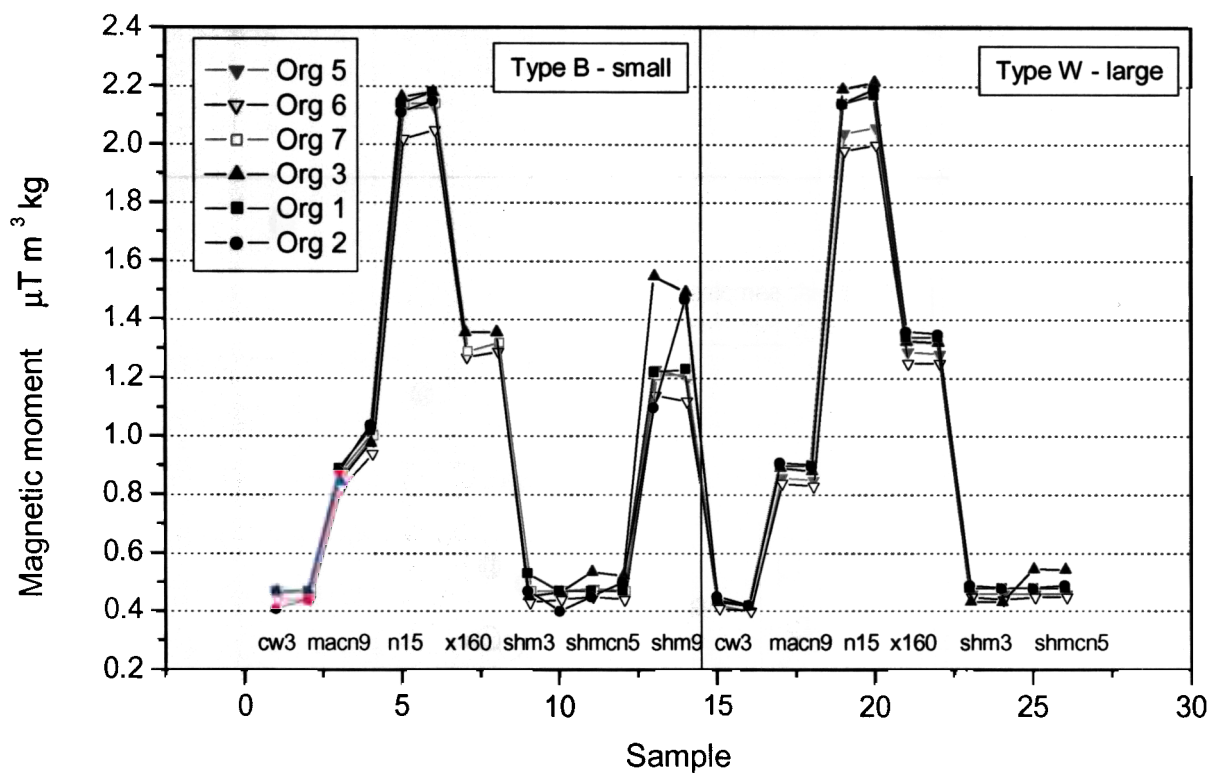
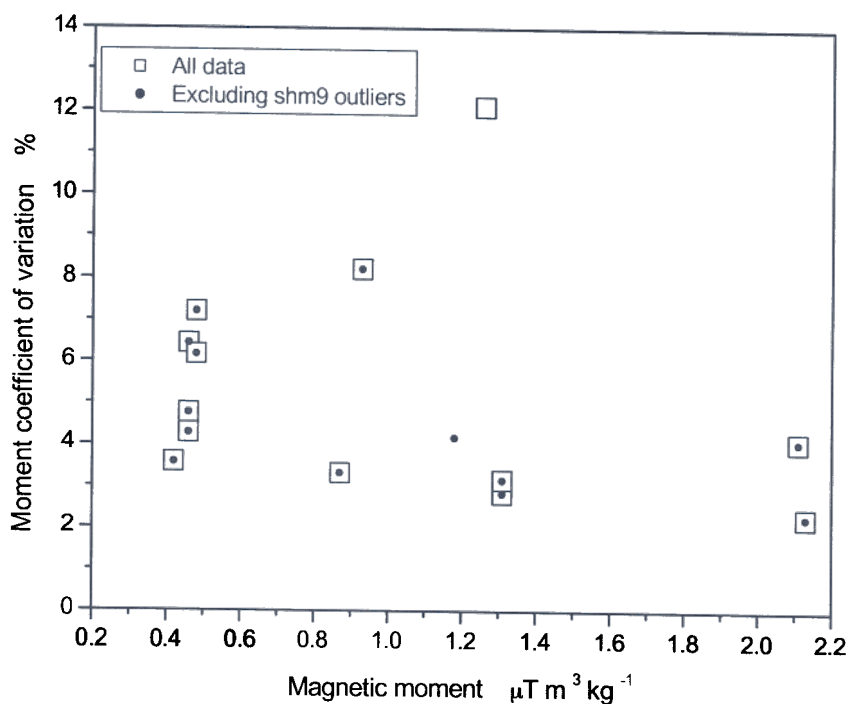
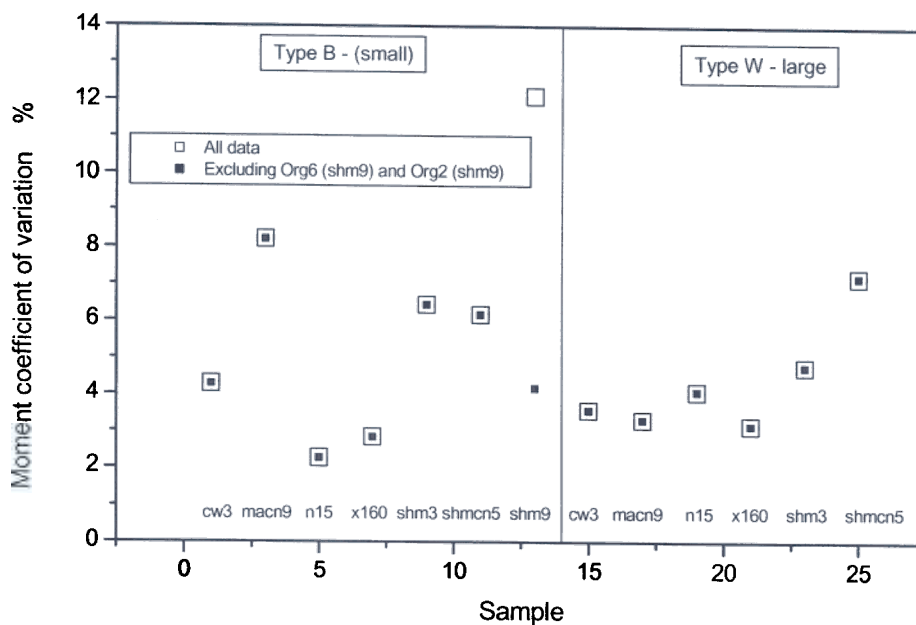


Fig 4 Comparative plot of magnetic moment data.



Coefficient of variation of magnetic moment results plotted against magnetic moment.



Coefficient of variation of magnetic moment results plotted against sample type.

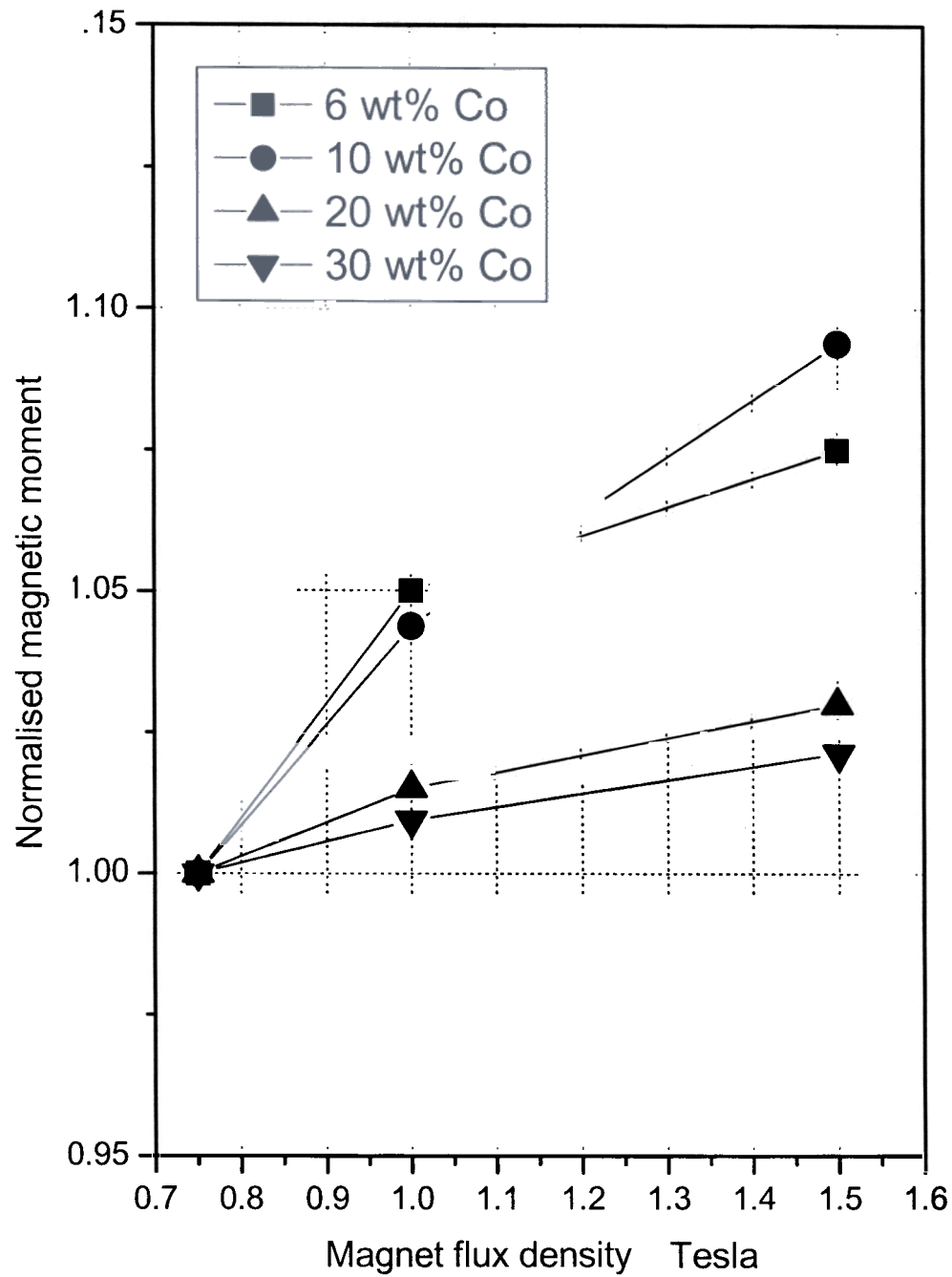


Fig 7 Effect of magnet field strength on measured values of magnetic moment (from ref 2)

There is some indication that organisation 6 had lower moment values than the other participants. This may be due to the flux density in the LDJ equipment being lower (0.75 Tesla) compared with the Setaram equipment used by other participants (1.0 Tesla). It is already known [2] that the measured moment is dependent on magnet field strength with a 5% increase noted for 6%Co hardmetals when the field strength is increased from 0.75 to 1.0 Tesla (Fig 7).

4 SUMMARY

For hardmetals with coercivity values less than 30 kA m⁻¹ the uncertainty in measurement (coefficient of variation) associated with interlaboratory reproducibility is between 1 - 2%. For materials with higher coercivities there is some indication that a higher uncertainty is likely (up to 5%).

For magnetic moment values the uncertainties associated with interlaboratory reproducibility are higher than those for coercivity, about 3-4% and sample size may cause problems when it is small. There is also a likely effect of field strength that can systematically affect the result – see reference 2 for quantification of this effect in different cobalt content hardmetals.

5 REFERENCES

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- 2 B Roebuck. Magnetic Moment (Saturation) Measurements on Hardmetals. Int. J. Refractory Metals and Hard Mater., 14, 1996, 419-424.

6 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.

APPENDIX A

Magnetic Measurements

Individual Results

Org 1

Material	Code	Sample size	Coecivity Oersteds A	B	D	Oersteds mean	kA/m mean	magnetic moment A	B	as%Co mean	magnetic moment microT.m^-3.kg^-1 normalised	
cw3	WCQ/6/5	B	182			182	14.5	2.92		2.92	4.6	0.47
cw3	WCQ/6/7	B	166			166	13.2	2.92		2.92	4.6	0.47
macn9	WCM/43/31	B	247			247	19.6	5.53		5.53	2.4	0.89
macn9	WCM/43/34	B	270			270	21.5	6.34		6.34	2.1	1.02
n15	WCP/4/15	B	152			152	12.1	13.30		13.30	1.0	2.14
n15	WCP/4/47	B	151			151	12.0	13.53		13.53	1.0	2.18
x160	WCK/6/17	B	178			178	14.2					
x160	WCK/6/18	B	132			132	10.5					
shm3	WCW/8/11	B	210			210	16.7	3.27		3.27	4.1	0.53
shm3	WCW/8/15	B	204			204	16.2	2.92		2.92	4.6	0.47
shm3cn5	WCW/11/15	B	187			187	14.9	2.93		2.93	4.5	0.47
shm3cn5	WCW/11/18	B	201			201	16.0	2.90		2.90	4.6	0.47
shm9	WCW/6/7	B	308			308	24.5	7.56		7.56	1.8	1.22
shm9	WCW/6/8	B	316			316	25.1	7.61		7.61	1.7	1.23
cw3	WCQ/7/1	W	315			315	25.1	2.73		2.73	4.9	0.44
cw3	WCQ/7/7	W	328			328	26.1	2.61		2.61	5.1	0.42
macn9	WCM/42/4	W	347			347	27.6	5.58		5.58	2.4	0.90
macn9	WCM/42/6	W	350			350	27.8	5.57		5.57	2.4	0.90
n15	WCP/5/7	W	163			163	13.0	13.27		13.27	1.0	2.14
n15	WCP/5/10	W	169			169	13.4	13.46		13.46	1.0	2.17
x160	WCK/5/6	W	219			219	17.4	8.35		8.35	1.6	1.34
x160	WCK/5/10	W	219			219	17.4	8.34		8.34	1.6	1.34
shm3	WCW/12/5	W	345			345	27.4	3.01		3.01	4.4	0.48
shm3	WCW/12/6	W	365			365	29.0	3.00		3.00	4.4	0.48
shm3cn5	WCW/10/4	W	306			306	24.3	2.97		2.97	4.5	0.48
shm3cn5	WCW/10/6	W	293			293	23.3	2.96		2.96	4.5	0.48

Org 2

Material	Code	Sample size	Coecivity Oersted				Mean	kA/m mean	magnetic moment		as%Co mean	magnetic moment microT.m^-3.kg^-1	
			A	B	C	D			A	B		normalised	
cw3	WCQ/6/5	B	260	274			267	21.2	2.56		2.56	5.1	0.41
cw3	WCQ/6/7	B	270	285			278	22.1	2.72		2.72	4.8	0.44
macn9	WCM/43/31	B	321	328			325	25.8	5.49		5.49	2.4	0.88
macn9	WCM/43/34	B	328	334			331	26.3	6.49		6.49	2.0	1.04
n15	WCP/4/15	B	163	166			165	13.1	13.13		13.13	1.0	2.11
n15	WCP/4/47	B	162	164			163	13.0	13.35		13.35	1.0	2.15
x160	WCK/6/17	B	217	220			219	17.4					
x160	WCK/6/18	B	215	219			217	17.3					
shm3	WCW/8/11	B	297	306			302	24.0	2.94		2.94	4.5	0.47
shm3	WCW/8/15	B	274	298			286	22.8	2.5		2.5	5.3	0.40
shm3	WCW/11/15	B	271	277			274	21.8	2.78		2.78	4.7	0.45
shm3	WCW/11/18	B	269	280			275	21.8	3.1		3.1	4.2	0.50
shm9	WCW/6/7	B	398	402			400	31.8	6.83		6.83	1.9	1.10
shm9	WCW/6/8	B	318	347			333	26.5	9.16		9.16	1.4	1.47
cw3	WCQ/7/1	W	359	363			361	28.7	2.77		2.77	4.7	0.45
cw3	WCQ/7/7	W	366	372			369	29.4	2.61		2.61	5.0	0.42
macn9	WCM/42/4	W	356	357			357	28.4	5.63		5.63	2.3	0.91
macn9	WCM/42/6	W	352	354			353	28.1	5.6		5.6	2.3	0.90
n15	WCP/5/7	W	172	174			173	13.8	13.29		13.29	1.0	2.14
n15	WCP/5/10	W	172	174			173	13.8	13.62		13.62	1.0	2.19
x160	WCK/5/6	W	228	230			229	18.2	8.44		8.44	1.6	1.36
x160	WCK/5/10	W	228	230			229	18.2	8.4		8.4	1.6	1.35
shm3	WCW/12/5	W	390	398			394	31.3	3.04		3.04	4.3	0.49
shm3	WCW/12/6	W	389	399			394	31.3	2.99		2.99	4.4	0.48
shm3	WCW/10/4	W	336	339			338	26.8	2.96		2.96	4.4	0.48
shm3	WCW/10/6	W	338	339			339	26.9	3.07		3.07	4.3	0.49

Org 3

Material	Code	Sample size	Coecivity Oersteds				Mean	kA/m mean	moment (161 = pure Co)		mean	magnetic moment			
			A	B	C	D			A	B		Equiv. Co content	normalised	microT.m ⁻³ .kg ⁻¹	
cw3	WCQ/6/5	B	355	349	342	334	345	27.4	157.28		157.3	2.9	4.6	0.47	cw3
cw3	WCQ/6/7	B	352	350	334	350	347	27.6	157.28		157.3	2.9	4.6	0.47	cw3
macn9	WCM/43/31	B	355	358	352	354	355	28.2	94.08		94.1	5.3	2.6	0.85	macn9
macn9	WCM/43/34	B	364	366	357	360	362	28.8	108.6		108.6	6.1	2.2	0.98	macn9
n15	WCP/4/15	B	165	165.6	165.7		165	13.2	144.3		144.3	13.4	1.0	2.16	n15
n15	WCP/4/47	B	163.8	163.1	163.1	163.6	163	13.0	145.3		145.3	13.5	1.0	2.18	n15
x160	WCK/6/17	B	230	231	231	231	231	18.4	135.7		135.7	8.4	1.6	1.36	x160
x160	WCK/6/18	B	230	230	231	231	231	18.3	135.7		135.7	8.4	1.6	1.36	x160
shm3	WCW/8/11	B	413	405	397	400	404	32.1	150.4		150.4	2.8	4.8	0.45	shm3
shm3	WCW/8/15	B	411	396	395	376	395	31.4	155.1		155.1	2.9	4.7	0.47	shm3
shmcn5	WCW/11/15	B	337	341	332	325	334	26.6	107.1		107.1	3.3	4.0	0.54	shmcn5
shmcn5	WCW/11/18	B	339	335	324	329	332	26.4	104.7		104.7	3.3	4.1	0.52	shmcn5
shm9	WCW/6/7	B	489	492	494	483	490	38.9	172.1		172.1	9.6	1.4	1.55	shm9
shm9	WCW/6/8	B	496	498	473	473	485	38.6	166.1		166.1	9.3	1.4	1.49	shm9
cw3	WCQ/7/1	W	371	369	366	368	369	29.3	144.7		144.7	2.7	5.0	0.43	cw3
cw3	WCQ/7/7	W	378	378	380	384	380	30.2	139.1		139.1	2.6	5.2	0.42	cw3
macn9	WCM/42/4	W	362	363	359	357	360	28.7	99.24		99.2	5.5	2.4	0.89	macn9
macn9	WCM/42/6	W	358	353	352	353	354	28.2	98.02		98.0	5.5	2.5	0.88	macn9
n15	WCP/5/7	W	168.8	169.2	169.9	169.6	169	13.5	146.1		146.1	13.6	1.0	2.19	n15
n15	WCP/5/10	W	168.9	169.4	168.2	169	169	13.4	147.7		147.7	13.8	1.0	2.22	n15
x160	WCK/5/6	W	231	232	232	232	232	18.4	132.6		132.6	8.2	1.6	1.33	x160
x160	WCK/5/10	W	231	232	232	233	232	18.5	132.2		132.2	8.2	1.6	1.32	x160
shm3	WCW/12/5	W	395	408	408	395	402	31.9	144.6		144.6	2.7	5.0	0.43	shm3
shm3	WCW/12/6	W	404	403	407	409	406	32.3	144.3		144.3	2.7	5.0	0.43	shm3
shmcn5	WCW/10/4	W	350	341	348	348	347	27.6	109.3		109.3	3.4	4.0	0.55	shmcn5
shmcn5	WCW/10/6	W	342	345	344	344	344	27.3	108.9		108.9	3.4	4.0	0.54	shmcn5

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Material	Code	Sample size	Coecivity Oersteds				Mean	kA/m mean	Magnetic moment		
			A	B	C	D			A	B	mean
cw3	WCQ/6/5	B	330				330	26.3			
cw3	WCQ/6/7	B	330				330	26.3			
macn9	WCM/43/31	B	350				350	27.8			
macn9	WCM/43/34	B	360				360	28.6			
n15	WCP/4/15	B	168				168	13.4			
n15	WCP/4/47	B	166				166	13.2			
x160	WCK/6/17	B	225				225	17.9			
x160	WCK/6/18	B	225				225	17.9			
shm3	WCW/8/11	B	390				390	31.0			
shm3	WCW/8/15	B	370				370	29.4			
shmcn5	WCW/11/15	B	340				340	27.0			
shmcn5	WCW/11/18	B	325				325	25.9			
shm9	WCW/6/7	B	490				490	39.0			
shm9	WCW/6/8	B	425				425	33.8			
cw3	WCQ/7/1	W	360				360	28.6			
cw3	WCQ/7/7	W	360				360	28.6			
macn9	WCM/42/4	W	360				360	28.6			
macn9	WCM/42/6	W	360				360	28.6			
n15	WCP/5/7	W									
n15	WCP/5/10	W									
x160	WCK/5/6	W	174				174	13.8			
x160	WCK/5/10	W	174				174	13.8			
shm3	WCW/12/5	W	380				380	30.2			
shm3	WCW/12/6	W	390				390	31.0			
shmcn5	WCW/10/4	W	345				345	27.4			
shmcn5	WCW/10/6	W	345				345	27.4			

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Material	Code	Sample size	Coecivity Oersteds		C	D	Mean	kA/m mean	saturation (4pisigma)		mean	magnetic moment microT.m ⁻³ .kg ⁻¹	
			A	B					A	B		normalised	
cw3	WCQ/6/5	B	350	354			352	28.0	57.7	59.1	58.4	4.6	0.46
cw3	WCQ/6/7	B	349	356			352.5	28.0	59.1	59.4	59.25	4.5	0.47
macn9	WCM/43/31	B	354	354			354	28.2	110	111.1	110.55	2.4	0.88
macn9	WCM/43/34	B	364	366			365	29.0	128.3	126.5	127.4	2.1	1.01
n15	WCP/4/15	B	166	166			166	13.2	266.3	266.6	266.45	1.0	2.12
n15	WCP/4/47	B	164	164			164	13.0	271.5	264.7	268.1	1.0	2.13
x160	WCK/6/17	B	226	227			226.5	18.0					
x160	WCK/6/18	B	225	225			225	17.9					
shm3	WCW/8/11	B	409	426			417.5	33.2	58.9	59.2	59.05	4.5	0.47
shm3	WCW/8/15	B	402	419			410.5	32.7	57.4	60.3	58.85	4.5	0.47
shmcn5	WCW/11/15	B	335	341			338	26.9	59.4	61.4	60.4	4.4	0.48
shmcn5	WCW/11/18	B	331	338			334.5	26.6	58.3	59.1	58.7	4.5	0.47
shm9	WCW/6/7	B	492	510			501	39.9	154.5	155.2	154.85	1.7	1.23
shm9	WCW/6/8	B	501	532			516.5	41.1	149.1	151.4	150.25	1.8	1.20
cw3	WCQ/7/1	W	372	373			372.5	29.6	52.8	52.8	52.8	5.0	0.42
cw3	WCQ/7/7	W	381	386			383.5	30.5	50.6	50.7	50.65	5.3	0.40
macn9	WCM/42/4	W	356	356			356	28.3	107.5	107.4	107.45	2.5	0.86
macn9	WCM/42/6	W	351	353			352	28.0	106.4	106.3	106.35	2.5	0.85
n15	WCP/5/7	W	169	169			169	13.4	256.4	255.4	255.9	1.0	2.04
n15	WCP/5/10	W	169	169			169	13.4	258.3	258.3	258.3	1.0	2.06
x160	WCK/5/6	W	226	226			226	18.0	162	161.4	161.7	1.6	1.29
x160	WCK/5/10	W	227	227			227	18.1	161	161	161	1.7	1.28
shm3	WCW/12/5	W	406	409			407.5	32.4	58.2	58.2	58.2	4.6	0.46
shm3	WCW/12/6	W	407	410			408.5	32.5	57.8	58	57.9	4.6	0.46
shmcn5	WCW/10/4	W	341	343			342	27.2	58.3	58.3	58.3	4.6	0.46
shmcn5	WCW/10/6	W	341	344			342.5	27.2	58.3	58.2	58.25	4.6	0.46

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Material	Code	Sample size	Coecivity Oersteds		C	D	Mean	kA/m mean	magnetic moment		magnetic moment microT.m ⁻³ .kg ⁻¹	
			A	B					A	B	mean	normalised
cw3	WCQ/6/5	B							0.44		0.44	4.6
cw3	WCQ/6/7	B							0.44		0.44	4.6
macn9	WCM/43/31	B							0.82		0.82	2.5
macn9	WCM/43/34	B							0.94		0.94	2.1
n15	WCP/4/15	B							2.02		2.02	1.0
n15	WCP/4/47	B							2.05		2.05	1.0
x160	WCK/6/17	B							1.27		1.27	1.6
x160	WCK/6/18	B							1.29		1.29	1.6
shm3	WCW/8/11	B							0.43		0.43	4.7
shm3	WCW/8/15	B							0.44		0.44	4.6
shmcn5	WCW/11/15	B							0.45		0.45	4.5
shmcn5	WCW/11/18	B							0.44		0.44	4.6
shm9	WCW/6/7	B							1.14		1.14	1.8
shm9	WCW/6/8	B							1.12		1.12	1.8
cw3	WCQ/7/1	W							0.41		0.41	4.9
cw3	WCQ/7/7	W							0.4		0.4	5.1
macn9	WCM/42/4	W							0.84		0.84	2.4
macn9	WCM/42/6	W							0.83		0.83	2.4
n15	WCP/5/7	W							1.98		1.98	1.0
n15	WCP/5/10	W							2		2	1.0
x160	WCK/5/6	W							1.25		1.25	1.6
x160	WCK/5/10	W							1.25		1.25	1.6
shm3	WCW/12/5	W							0.45		0.45	4.5
shm3	WCW/12/6	W							0.44		0.44	4.6
shmcn5	WCW/10/4	W							0.45		0.45	4.5
shmcn5	WCW/10/6	W							0.45		0.45	4.5

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Material	Code	Sample size	Coecivity Oersteds A	C	D	Mean	kA/m mean	moment (as % Co)		mean	magnetic moment microT.m ⁻³ .kg ⁻¹	
								A	B		normalised	
cw3	WCQ/6/5	B					26.9	2.9		2.9	4.6	0.47
cw3	WCQ/6/7	B					27	2.9		2.9	4.6	0.47
macn9	WCM/43/31	B					27.6	5.4		5.4	2.5	0.87
macn9	WCM/43/34	B					28.5	6.2		6.2	2.1	1.00
n15	WCP/4/15	B					13.2	13.3		13.3	1.0	2.14
n15	WCP/4/47	B					13	13.3		13.3	1.0	2.14
x160	WCK/6/17	B					17.8	8		8	1.7	1.29
x160	WCK/6/18	B					17.8	8.2		8.2	1.6	1.32
shm3	WCW/8/11	B					31.4	2.9		2.9	4.6	0.47
shm3	WCW/8/15	B					31.2	2.9		2.9	4.6	0.47
shmcn5	WCW/11/15	B					26.3	2.9		2.9	4.6	0.47
shmcn5	WCW/11/18	B					26	2.9		2.9	4.6	0.47
shm9	WCW/6/7	B					38.2	7.5		7.5	1.8	1.21
shm9	WCW/6/8	B					38.2	7.5		7.5	1.8	1.21
cw3	WCQ/7/1	W					29					
cw3	WCQ/7/7	W					30.5					
macn9	WCM/42/4	W					28.4					
macn9	WCM/42/6	W					28.1					
n15	WCP/5/7	W					13.5					
n15	WCP/5/10	W					13.4					
x160	WCK/5/6	W					18					
x160	WCK/5/10	W					18					
shm3	WCW/12/5	W					32.2					
shm3	WCW/12/6	W					32.5					
shmcn5	WCW/10/4	W					27					
shmcn5	WCW/10/6	W					27					