

Magnetic Moment (Saturation) Measurements on Hardmetals

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ABSTRACT

This report summarises the background to the use of appropriate units for the measurement of magnetic moment (saturation) in hardmetals. It also discusses the methods used for correlating composition/structure with magnetic properties and indicates the theoretical ranges likely to be obtained in typical industrial products. It includes comparative data obtained on two different measurement systems on both hardmetals and synthetic Co, Co-Ni and Ni alloys containing W and C in solution.

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BACKGROUND

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. If interpreted correctly, they can be linked to the cobalt composition and hence overall properties and performance. But, 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.

This report thus discusses the use of magnetic moment (saturation) measurements on hardmetals. It gives the background to the correct use of units and the different methods for expressing the results on typical hardmetals.

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 [1,2] 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)
σ	=	Magnetic moment/unit weight (intensity of magnetisation/unit wt)
σ	=	$\frac{I}{\rho}$ 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

	Non-SI metric	SI
$4\pi I, J_s$ Saturation magnetic polarisation	gauss	tesla
$4\pi \sigma$ Magnetic saturation/ unit wt	gauss cm ³ g ⁻¹	tesla m ³ kg ⁻¹
σ Magnetic moment/ unit wt	gauss cm ³ g ⁻¹	tesla m ³ 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 [3]

Density, ρ

$$= 8850 \text{ kg m}^{-3}$$

Saturation induction/unit volume, $4\pi I_{Co}$

$$= 17870 \text{ gauss} = 1.787 \text{ tesla}$$

Saturation induction (magnetic saturation)/unit wt, $4\pi\sigma_{Co}$

$$= 201.9 \mu\text{T m}^3 \text{ kg}^{-1}$$

Magnetic moment/unit wt, σ_{Co}

$$= 16.1 \mu\text{T m}^3 \text{ kg}^{-1}$$

MAGNETIC SATURATION AND MOMENT MEASUREMENTS

Nominally pure Co binder-phase

There are various methods by which magnetic saturation measurements can be made on hardmetals. One of these methods, used by Cutanit Ltd (now Plansee UK Ltd), involved weighing the hardmetal sample in air and then in a strong magnetic field - the Sucksmith balance method [3]. The field strength has to be sufficiently large to produce close to full saturation of the cobalt binder-phase. In practice it is quite difficult to produce equipment which fully saturates the cobalt phase. Thus the use of different equipment with different field strengths will give slightly different results. These differences can in principle be rationalised by the use of reference samples.

The saturation value of the hardmetal is then determined by comparison of the apparent change in weight produced by the field gradient on the hardmetal with that produced by insertion of a sample of pure cobalt in the same field gradient. For example, the saturation value, $4\pi\sigma$, of a tungsten carbide/10 wt% cobalt hardmetal in which the cobalt contained little or no tungsten in solution was measured at Cutanit in a large electromagnet which could fully saturate the hardmetal [4] and gave the following result.

$$\begin{aligned} 4\pi\sigma_H &= 202 \text{ gauss cm}^3 \text{ g}^{-1} \\ &= 20.2 \text{ } \mu\text{T m}^3 \text{ kg}^{-1} \end{aligned}$$

and thus the magnetic moment, σ_H , of the hardmetal = $1.61 \text{ } \mu\text{T m}^3 \text{ kg}^{-1}$.

Furthermore, the saturation induction/unit wt of hardmetal, $4\pi\sigma_H$, = saturation induction/unit wt of cobalt in the hardmetal, $4\pi\sigma_{Co}$, multiplied by the wt fraction of cobalt in the hardmetal (w_f), ie

$$4\pi\sigma_H = 4\pi\sigma_{Co} w_f$$

where σ_{Co} is the magnetic moment/unit wt of the cobalt present in the hardmetal.

Thus for the hardmetal described above

$$202 = 4 \times \pi \times \sigma_{Co} \times 0.1$$

Therefore, the saturation induction/unit wt, for the cobalt in the hardmetal was given by

$$\begin{aligned} 4\pi\sigma_{Co} &= 2020 \text{ gauss cm}^3 \text{ g}^{-1} \\ &= 202 \text{ } \mu\text{T m}^3 \text{ kg}^{-1} \end{aligned}$$

which agrees very well with the reference value of $2019 \text{ gauss cm}^3 \text{ g}^{-1}$ ($202 \text{ } \mu\text{T m}^3 \text{ kg}^{-1}$) quoted for pure cobalt [3].

Practical Co binder-phases

If the cobalt in the hardmetal contains tungsten in solution then the saturation value for the hardmetal can be calculated because [1,2]

$$\sigma_B = \sigma_{Co} - 0.275 m_w$$

where σ_{Co} is the magnetic moment/unit wt of pure cobalt, σ_{B} is the magnetic moment/unit wt of the Co binder-phase, and m_{W} is the wt % W dissolved in the cobalt.

For example, if the tungsten carbide/10 wt % cobalt hardmetal described above contained 5 wt % W dissolved in the binder then the saturation moment/unit wt of the cobalt binder-phase, σ_{B} , is given by

$$\begin{aligned}\sigma_{\text{B}} &= \sigma_{\text{Co}} - 5 \times 0.275 \\ &= 14.7 \mu\text{T m}^3 \text{ kg}^{-1}\end{aligned}$$

and the saturation induction/unit wt of hardmetal by

$$\begin{aligned}4\pi\sigma_{\text{H}} &= 4\pi\sigma_{\text{B}}w_{\text{f}} \\ &= 18.5 \mu\text{T m}^3 \text{ kg}^{-1}\end{aligned}$$

and the magnetic moment/unit wt of the hardmetal, σ_{H} is thus

$$\begin{aligned}&= 18.5/4\pi \\ &= 1.47 \mu\text{T m}^3 \text{ kg}^{-1}\end{aligned}$$

It is clear from the above text that it is important not be confused between the saturation or moment values that can be quoted for hardmetals.

- One refers to the magnetic saturation or moment value of the hardmetal
- The other refers to the magnetic saturation or moment value of the Co binder-phase (Co-W-C) in the hardmetal
- Finally, magnetic moment is converted to magnetic saturation by 4π multiplication

Also saturation values are sometimes expressed as a percentage of the maximum expected for a nominally pure Co binder phase. For example, in the case above the saturation can have the value of $(14.7/16.1) \times 100\% = 91.3\%$.

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

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

* Binder assumed to be pure Co

Table 2
Illustrative table of magnetic saturation and moment per unit wt
pre SI units - gauss cm³ g⁻¹

	5 wt% Co*	10 wt% Co*	15 wt% Co*
Hardmetal			
magnetic saturation, $4\pi\sigma$	101	202	303
magnetic moment, σ	8.0	16.1	24.1
Binder-phase			
magnetic saturation, $4\pi\sigma$	2020	2020	2020
magnetic moment, σ	161	161	161

MEASUREMENT RANGES

In practical materials there is a range of magnetic saturation and moment values associated with a variation in the carbon content of the hardmetal.

In most hardmetals the binder contains W and C in solution. Presence of C does not affect the cobalt magnetic saturation and moment values but W decreases it. The decrease can be represented by

$$4\pi\sigma_B = 4\pi(\sigma_{Co} - 0.275 m_w)$$

Where $4\pi\sigma_{Co}$ is $202 \mu T m^3 kg^{-1}$ and m_w is the wt% W in the Co binder-phase.

When $4\pi\sigma_B$ attains a value of about $160 \mu T m^3 kg^{-1}$ eta-phase begins to form and so the range $202-160 \mu T m^3 kg^{-1}$ for the magnetic saturation of the cobalt phase defines the two-phase field in WC/Co hardmetals.

Example

For a 6% Co hardmetal the magnetic saturation value is in the range

$$202 \times 0.06 - 160 \times 0.06 \mu T m^3 kg^{-1}$$

$$\text{ie } 12.1-9.6 \mu T m^3 kg^{-1}$$

Alternatively, if a 6% Co hardmetal has a magnetic saturation value of $11 \mu T m^3 kg^{-1}$

$$\text{then } 4\pi\sigma_B = 11/0.06 = 183.3 \mu T m^3 kg^{-1}$$

$$\text{Therefore } m_w = \frac{202-183.3}{4\pi \times 0.275} = 5.4 \text{ wt\%}.$$

Thus the W content of the Co-W-C binder can in principle be calculated from the hardmetal magnetic saturation or moment value.

Summary

There is thus a range of values of magnetic moment and saturation in typical hardmetals as can be seen in this summary table.

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

	5 wt% Co	10 wt% Co	15 wt% Co
Hardmetal			
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
Binder-phase			
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

Table 4
Typical ranges of magnetic saturation and moment values
 pre SI units - $\text{gauss cm}^3 \text{ g}^{-1}$

	5 wt% Co	10 wt% Co	15 wt% Co
Hardmetal			
magnetic saturation, $4\pi\sigma$	80-101	161-202	241-303
magnetic moment, σ	6.4-8.0	12.8-16.1	19.2-24.1
Percentage saturation	80-100	80-100	80-100
Binder-phase			
magnetic saturation, $4\pi\sigma$	1600-2020	1600-2020	1600-2020
magnetic moment, σ	128-161	128-161	128-161
Percentage saturation	80-100	80-100	80-100

ADDITIONAL BINDER-PHASE SOLUTES

The previous discussion has assumed that the binder-phase in WC/Co hardmetals is a Co-W-C alloy. In practice other elements can be present, particularly Fe, which can have an effect on the magnetic moment which makes precise calculations difficult.

For example, the equation relating the change in magnetic moment of the binder phase with W additions

$$\sigma_B = \sigma_{Co} + A m_W$$

is probably acceptable for elements other than W with the following values for A [3].

Table 5

Element	A T kg ⁻¹ /wt% addition
W	-0.28
Cr	-0.60
Fe	+0.13
Mo	-0.24
Ni	-0.11

No data for V or Ta could be found in the literature. These are important elements which could be present in small amounts in the binder phase.

It is also probably reasonable to assume that in dilute Co-W-X alloys that the effects of different elements on A are additive.

For example a typical hardmetal the binder might contain about 2wt% of Fe. The effect of Fe on magnetic moment is opposite to that for W at about half the strength. This leads to a correction of about +1% on the wt% W figure calculated for the magnetic moment, assuming a Co-W binder.

MEASUREMENTS AT NPL

Commercial Equipment

At NPL a saturation induction measuring system (LDJ Electronics Inc) is used. Comparisons have been made between measurements made on Co-W-C, Co-Ni-W-C and Ni-W-C alloys both at Cutanit Ltd (now Plansee UK Ltd) and NPL. The results are shown in Fig 1. A figure of $5.5 \mu\text{T m}^3 \text{ kg}^{-1}$ was assumed for the pure Ni sample which was used to calibrate the equipment at NPL. Measurements on similar Ni samples at Cutanit in the large electromagnet gave an average value of $5.55 \mu\text{T m}^3 \text{ kg}^{-1}$.

A similar comparison was made on Ni, Co-Ni and Co bonded hardmetals, with a range of C contents. The results are shown in Fig 2 where it can be seen that the Cutanit equipment gave higher values than the LDJ equipment. The difference was possibly due to a higher field strength in the Cutanit electromagnet. The field strength in the LDJ equipment is a nominal 0.75T. The strength of the electromagnet was not known accurately but was almost certainly higher than 0.75T. The electromagnet gave values for the Co alloys and hardmetals which were comparable with those quoted in Bozorth (3) and are thus thought to be accurate. The LDJ equipment gave values which were different to a degree which was dependent on the composition.

It was also found that if testpieces with a large aspect ratio (>3 to 1) were used then a 1-3% variation in result was found according to the orientation of the testpiece with regard to the magnetising pole pieces.

Reference Measurements

To examine the effects of field strength on magnetic moment measurements in representative hardmetals several measurements were made on rectangular testpieces (about 10 mm x 6 mm x 6 mm) in an electromagnet at NPL following the guidelines in IEC 404 pt 5. The

results are shown in Table 6. An effect of field strength can be seen which is significant with respect to the control of carbon content. For example for 6% Co hardmetals the theoretical range of moment values is about $0.96\text{--}0.72\text{ T kg}^{-1}$ across the two-phase (WC/Co) field. For a hardmetal with a nominal 6wt% Co (probably slightly lower than 6 in practice) the range of moment values was found to be between 0.8–0.86 for applied magnetic fields varying from 0.75–1.0T.

Table 6

Nominal Co content, wt %	Density, ρ Mg m^{-3}	NPL (LDJ) $\mu\text{T m}^3 \text{kg}^{-1}$		NPL Reference - $\mu\text{T m}^3 \text{kg}^{-1}$		
		Field Strength	0.75 T	0.75 T	1.0 T	1.5 T
6	14.93	0.82		0.8	0.84	0.86
10	14.43	1.53		1.6	1.67	1.75
20	13.66	2.65		2.67	2.71	2.75
30	12.72	4.22		4.26	4.3	4.35

The results on the reference samples are shown plotted in Fig 3 against applied field strength with the moments normalised by the values at 0.75T.

It is thus probably desirable for industrial measurements to be compared using properly calibrated hardmetals for reference.

CONCLUSIONS

The correct SI units to use for both magnetic moment or saturation are $\mu\text{T m}^3 \text{Kg}^{-1}$. To convert pre SI units of gauss (emu) $\text{cm}^3 \text{g}^{-1}$ to $\mu\text{T m}^3 \text{kg}^{-1}$ it is necessary to multiply the pre SI figure by a conversion factor of 0.1.

Magnetic moment (saturation) measurements can in principle be used to monitor the composition of the binder phase. However, in practice, for accurate correlations, it is necessary to have an independent analysis of the cobalt content of the hardmetal and ideally some information on the other solutes that might be present such as Fe, Ni, Cr etc. This is not always straightforward.

Calibrated reference samples which have been measured in equipment with a known field strength should be used for accurate measurements and care should be taken with the geometry and dimensions of the testpiece in relation to the field direction.

ACKNOWLEDGEMENTS

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LIST OF CAPTIONS

1. Comparison of magnetic moment measurements on Ni (W,C), Co (W,C) and Co-Ni (W,C) alloys at NPL and Cutanit Ltd.
2. Comparison of magnetic moment measurements on Ni, Co-Ni and Co bonded hardmetals at Cutanit Ltd and NPL.
3. Effect of applied field strength on measured values of moment (per unit wt of hardmetal) for four Co contents (6, 10, 20, 30%).

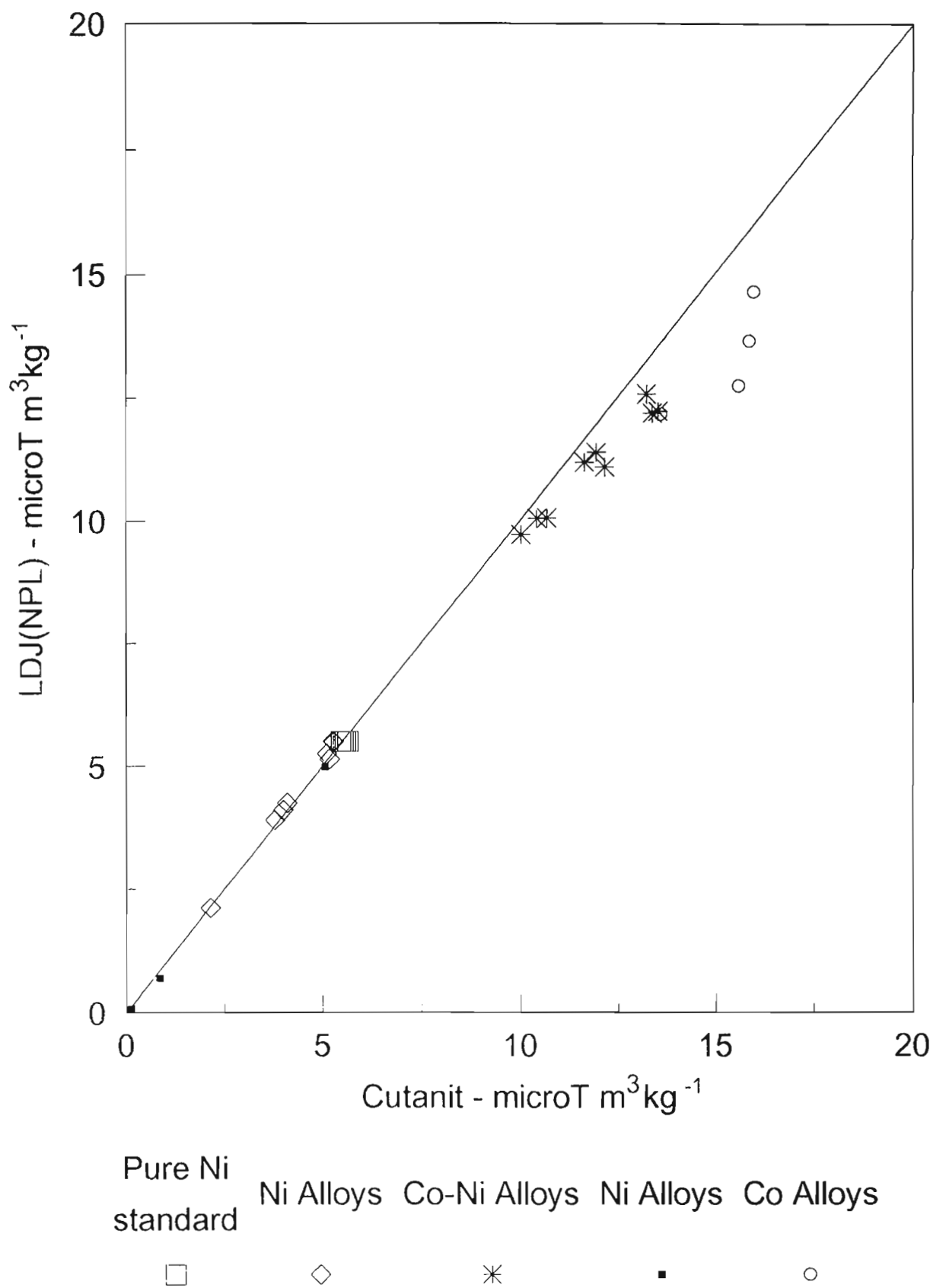
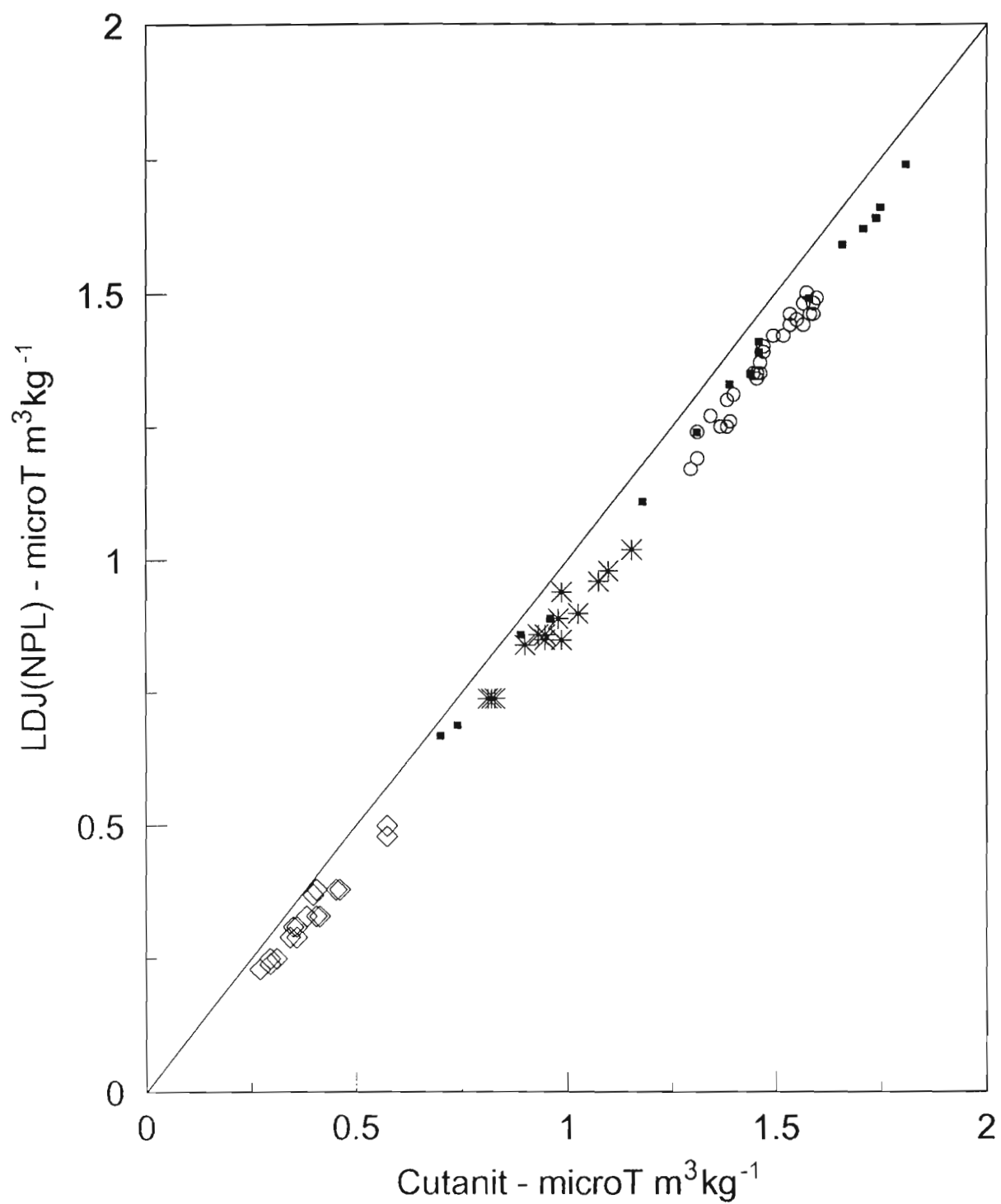


Fig 1

Comparison of magnetic moment measurements on Ni (W,C), Co (W,C) and Co-Ni (W,C) alloys at NPL and Cutanit Ltd.



Ni Hardmetals 10% Binder $\diamond$
 Co/Ni Hardmetals 10% Binder $*$
 Co Hardmetals 10% Binder $\circ$
 Co hardmetals 6-12% binder $\blacksquare$

Fig 2

Comparison of magnetic moment measurements on Ni, Co-Ni and Co bonded hardmetals at Cutanit Ltd and NPL.

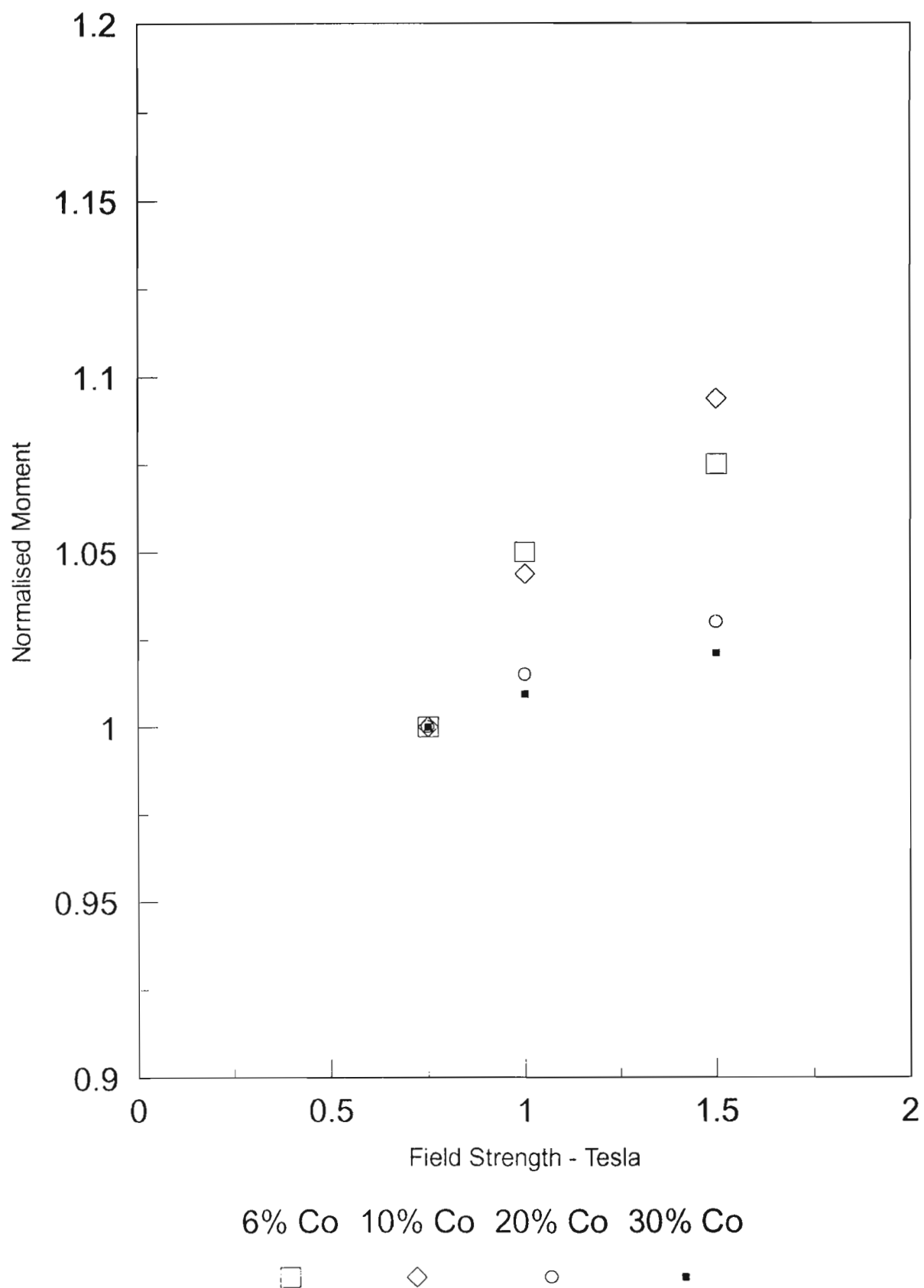


Fig 3 Effect of applied field strength on measured values of moment (per unit wt of hardmetal) for four Co contents (6, 10, 20, 30%).