

Characterisation of Baseline Hardmetals Using Property Maps

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ABSTRACT

Over thirty hardmetals supplied by industry were characterised for their microstructure and mechanical properties. The measurements were used to validate WC grain size and mechanical property determination methods. The data from the tests were also used to develop the concept of property maps where either physical or mechanical properties are mapped against key microstructural features, such as WC grain size and cobalt content. The property maps can be used both to benchmark new materials and for the purposes of quality control to ensure consistency of product.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Centre for Materials Measurement and Technology

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1 INTRODUCTION

New hardmetals based on WC/Co are evaluated by industry on a continuous basis, particularly to examine new kinds of powders, powder mixes and compositions. New materials need to be benchmarked against conventional materials for basic properties such as hardness, wear resistance and toughness. This task is lengthy and frequently difficult because of the lack of good data from validated measurement methods by which to make the comparisons. Microstructures also need to be quantified and there are no standardised techniques for WC grain size measurement. For this reason the UK hardmetal industry, through the Research Group of the British Hardmetal Industry, has worked in partnership with CMMT at NPL to characterise a range of conventional hardmetals for this baseline purpose. The UK DTI provided support for NPL for this activity through projects CAM3, CAM4 and CAM9 in the Advanced Materials Measurement Programme.

The materials for investigation were chosen to complement a series of 6 wt% Co hardmetals investigated previously [1]. They included a range of grain sizes and Co contents from 6-25 wt%. They also included materials with binder phases other than Co, i.e. Ni and Co/Ni and a TiC/Mo₂C/Ni hardmetal.

The structural characterisation exercise consisted of a measurement of WC grain size and size distribution. These measurements were then analysed for comparison with model predictions from an NDE measurement of magnetic coercivity. The coercivity data were provided by industry. The property characterisation exercise consisted of a measurement of hardness, toughness (by the Palmqvist method) and abrasion resistance. The measurements were used to construct "property maps". These maps allow the effects of differences in structure and properties to be easily compared and provide a benchmark for the evaluation of new materials.

2 MATERIALS AND MEASUREMENTS

2.1 MATERIALS

Thirty three hardmetals were supplied by industry. The codes and source details are given in Table 1 together with a chemical analysis (Vanadium was not determined). The chemical analyses were provided by Sandvik Hard Materials and H C Starck. Five of the hardmetals were manufactured with a Ni binder phase - codes; MAN6, MAN10, CWN8, DN6 and DN10 one contained a Co-Ni binder phase, code SHM5CN.

The nominal binder contents agree fairly well with the measured binder contents (Table 1) and thus for analysis of results measurements are grouped into categories of 6, 10, 15, 20 and 25% binder phase. Additional comments on individual sources are as follows:

Marshall's Hardmetals:

Sample MAN6 contained some Mo

Neepsend:

Sample N10 contained Cr, probably as grain refiner.

All samples were low in Fe.

Teco:

Sample TC6 contained Cr, probably as a grain refiner.

Samples T16D and T25D were higher in Fe than the average.

Sandvik HM:

Sample SHM5CN contained Co/Ni in the approximate ratio of 3/1. It also contained significant amounts of Cr and Mo.

Dymet:

The binder in DN6 was a Ni-Co alloy in the approximate ratio 95/5 (Ni/Co).

Kennametal:

Both TC222 and K3560 contained significant amounts of Fe and Mo.

2.2 MEASUREMENTS

Magnetic coercivity measurements were performed at Marshalls Hardmetals Ltd. Magnetic moment data (expressed as $\mu\text{T m}^3 \text{ kg}^{-1}$ of hardmetal) were obtained using the LDJ equipment at NPL. Some additional magnetic data was supplied by Sandvik Hard Materials together with chemical analysis. Chemical compositions were measured at Sandvik Hard Materials and H C Starck.

Grain size measurements were made using the linear intercept method from scanning electron micrographs.

Testpieces for Palmqvist toughness tests were polished and annealed at 800 °C for 1h in a vacuum. Tests were performed at applied loads of 30, 60 and 100 kgf due to the difficulty in obtaining cracks on some of the materials at the lower loads. Abrasion tests were performed on testpieces that had been diamond ground at NPL. Both SiO_2 and Al_2O_3 abrasives were used, following the ASTM B611 procedure.

3 RESULTS

3.1 CHEMICAL ANALYSES

The results of chemical analyses are given in Table 1.

3.2 DENSITY MEASUREMENTS

The density values are plotted in Fig 1 for each group of materials. Theoretical bounds are shown for hardmetals manufactured from pure WC (with assumed densities of either 15.55, 15.65 or 15.75 Mg m^{-3}) and pure Co (density of 8.9 Mg m^{-3}).

3.3 MAGNETIC MEASUREMENTS

The results of magnetic moment and coercivity measurements are given in Table 2 and Figs 2-3. The scatter in Fig 3 is caused by the variation in WC grain size at any given Co content.

The chemical analyses, density and magnetic measurements can be used to estimate the approximate carbon content of the materials, i.e. the position within the two-phase field. The results are summarised in Table 3.

3.4 STRUCTURE AND GRAIN SIZE MEASUREMENTS

SEM and optical micrographs of the materials are shown in Figs 4-37. The optical micrographs are at x1000 and x1600. All the materials were nominally two-phase except for sample SHMUF. This material contained eta-phase.

Figs 38-45 show plots of the number distributions of the intercept data. Fig 38 is for all the materials. Figs 39-45 are for groups of materials to allow the individual data to be seen more clearly. There is a very wide range of grain sizes in the materials from sample SHMUF with an arithmetic mean linear intercept (amli) of about 0.15 μm to UC9 with an amli of 4.9 μm .

The results of the grain size measurements are given in Table 4. This table includes the number of intercepts measured to obtain the arithmetic mean linear intercept. It also

includes columns for the inverse of the mean linear intercept and the inverse of the square root of the mean linear intercept as these parameters are used for analysing the data and developing property maps.

Figs 46-52 show plots of the size distributions of the intercept data where size probability was calculated from squaring the intercepts to give estimated values of area [ref]. Fig 46 is for all the materials. Figs 47-52 are for groups of materials to allow individual data to be seen more clearly. Fig 53 shows the size probability data compared with plots obtained from a model 3-D shape, a tetrakaidecahedron [2]. This method of presentation allows the width of the distribution to be estimated although there is some uncertainty arising from the shape of grains. Further work is needed to clarify this issue.

3.5 MECHANICAL PROPERTIES

3.5.1 Abrasion Tests

The results of the abrasion tests are given in Table 5. The abrasion resistance is expressed as volume loss in units of cm^3 . The table includes data for all the materials using an Al_2O_3 abrasive (standard) together with some results using a SiO_2 abrasive. Hardness and density measurements are also included in Table 5. Abrasion test results for a TiC/Mo₂C/Ni hardmetal are also included in Table 5.

The abrasion results are plotted against hardness in Fig 54, compared with tests on 6 wt% Co hardmetals reported previously. The TiC material and the WC materials with Ni and Ni/Co binders are separately identified. It can be seen that changing the binder-phase from Co to Ni has little effect on abrasion resistance for a given value of hardness in this test. However, changing the hard phase from WC to TiC does result in a significant deterioration in wear properties.

3.5.2 Hardness and Palmqvist Toughness Tests

Hardness and Palmqvist toughness test results are given in Table 6. The results include data from tests at HV30 or HV60 and HV100. The higher load was used because in some of the materials no cracks could be observed for the HV30 indents. The Palmqvist toughness data are plotted against hardness in Fig 55. Figure 55 shows a comparison with previous data on 6% and 10% Co baseline materials obtained at HV30. The HV30 data for DN10 and D10 are thought to be higher than the true values because of the difficulty of producing suitable cracks.

4 DISCUSSION AND PROPERTY MAPS

Two types of property map were considered.

In the first type the property of interest is plotted against a microstructural feature that controls that property. In this case two microstructural features were evaluated, WC grain size, d , and wt% cobalt content, W . It is recognised that other parameters are important, such as the composition of the cobalt binder phase or the size distribution of WC grains. However, for this report the property maps were developed assuming a composition approximately in the centre of the two-phase WC/Co region and assuming a conventional WC grain size distribution with the arithmetic number mean intercept, d , as the parameter characterising WC grain size.

The four properties that were compared with microstructure were:

Coercivity, K
Hardness, H

Abrasion Resistance, A
Palmqvist Toughness, T

Thus eight property maps based on microstructure were constructed:

K	v	d	K	v	W
H	v	d	H	v	W
A	v	d	A	v	W
T	v	d	T	v	W

The rationale behind the construction of the maps was to use the data from the CAM3/4 materials to generate equations relating each of the four properties to d and W. These equations were physically based where possible.

In the second type of property map each of the three mechanical properties were compared against each other in pairs to give three maps:

A	v	H	T	v	H	A	v	T
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Also Coercivity was compared with Hardness to give an additional map. Thus four in total.

4.1 MICROSTRUCTURE PROPERTY MAPS

4.1.1 Magnetic Properties

Grain size is usually related to coercivity using an inverse expression [3].

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

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. Previous work [3] found values of 1.79 for a and 10.9 for b for WC/6wt% Co hardmetals with values of K less than about 15 kA m⁻¹. Most of the material examined in the current work had coercivity values within the same range, except the two materials from Sandvik Hard Materials. The coercivity data from the current exercise were grouped into batches based on Co content as follows:

6% Co:	10% Co:	15% Co:	20% Co:	25% Co:
MA6	UC9	MA15	MA20	MA24
T6	G10	CW15F	CW20C	CW25C
N6	N10	CW15C	T20D	T25D
TC6	D10	M15		
TC222	MA10	G15		
	T	N15		
	K3560	T16D		
		D15		

Plots of coercivity versus the inverse grain size are shown in Fig 56 for each group together with a linear fit. The fitted values for the coefficients a and b for each Co group are:

Wt% Co	a	b
6	1.74	10.61
10	2.10	8.63
15	1.89	6.55
20	1.94	5.14
15	2.85	3.53

It can be seen that the a and b values for the 6wt% Co CAM3/4 materials are very similar to those obtained in earlier work [3]. Because the variation of a and b with Co content is reasonably linear, further analysis allows an expression to be written for the variation of coercivity, K, with grain size, d for $6 < \text{Co} < 25\text{wt}\%$ as follows:

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

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 .

Expression (2) can be plotted as a property map, Figs 57 and 58, bearing in mind the constraint that it has not been extensively validated for coercivity values greater than about 15 kA m^{-1} , ie equivalent to WC grain sizes (arithmetic linear intercept) less than about $0.8 \mu\text{m}$. Additional work is needed to evaluate the finer grained materials. Fig 57 plots expression (2) as $y = a + bx$ with x as $1/d$. Fig 58 plots expression (2) with $x(d)$ as a linear abscissa.

A property map using Co wt% content as the variable can also be plotted from expression (2). This is shown in Fig 59 for values of linear intercept WC grain size of 5, 2, 1, 0.75 and $0.5 \mu\text{m}$, respectively.

It is also necessary to be aware that the coercivity also varies with carbon content and W content of the binder-phase. The materials in the CAM3/4 exercise contained a range of carbon contents and this has not been allowed for in the construction of the property map in Figs 57 and 58. It has been assumed that the compositions are approximately in the centre of the two phase field. An estimate of uncertainty due to this source can be calculated from measurements of coercivity on materials examined in previous collaborative work with the BHA Research Group coded BH12C, BH6F and V1. BH12C and BH6F are 12 wt% and 6 wt% Co hardmetals, medium and fine grained respectively. Material V1 was similar to BH6F but contained 2wt% TaC. These materials were manufactured deliberately with a range of carbon contents. The coercivity values across the two-phase field were as follows:

BH6F	20-22 kA m^{-1}
V1	10-14 kA m^{-1}
BH12C	9-13 kA m^{-1}

Expression (2) can be used to calculate a mean WC intercept value of grain size and compared with these measured values as follows:

Code	Calculated WC Grain Size, μm^+	Measured WC mean intercept, μm
BH6F	0.50 - 0.56	0.4 - 0.5*
V1	0.7 - 1.1	1.1
BH12C	0.8 - 1.2	1.1 - 1.4

⁺Calculated using expression (2)

*Measured using transmission electron microscopy; probably underestimates mean size

It can be seen that the agreement is quite reasonable. The calculated size varies by about $\pm 20\%$ across the two phase field, whereas the measured variation is probably $\pm 10\%$. The

difference is thus probably due to variation in composition. Further work would be needed to refine expression (2) to allow for this effect.

A further aspect that is clear from inspecting the property maps in Figs 57 and 58 is that the coercivity measurements are fairly insensitive to changes in grain size as the mean value increases beyond about 3 μm .

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 contribute added uncertainty to the correlation between grain size and coercivity and need to be systematically examined.

4.1.2 Hardness

Hardness can be related to the inverse square root of the grain size using the Hall-Petch expression [3].

$$H = e + fd^{-0.5} \quad (3)$$

where e and f are constants, H is the hardness, HV30, and d is the WC arithmetic mean linear intercept in μm . The hardness data from the current exercise were plotted against $d^{-0.5}$ (Fig 60) and used to generate values for the coefficients e and f for each set of Co contents.

Further analysis allowed an expression to be written for the variation of hardness, H , with grain size, d , for $6 < \text{Co} < 25 \text{ wt\%}$ as follows:

$$H = (888 - 9.9 * \text{wt\% Co}) + \frac{(229 + 532 * \exp(-(\text{wt\% Co} - 6) / 6.7))}{\sqrt{d}} \quad (4)$$

Expression (4) can be plotted as property maps, Figs 61 and 62, bearing in mind it is not validated extensively for the finer grained materials. There is some evidence [3] that the Hall-Petch expression (Fig 61) is inaccurate for the finer grained materials. Further work is needed to assess materials with grain sizes less than 0.5 μm .

A property map using Co wt% content as the variable can also be plotted from expression (4): This is shown in Fig 63 for different values of the WC linear intercept grain size.

4.1.3 Abrasion Resistance

The results in Table 5 and Fig 54 show that the WC/Co hardmetals within the CAM3/4 materials set fall on the same trend line as the previously reported 6% wt Co hardmetals. Also the use of alternative binder phases such as Ni or Co/Ni alloys maintains the same correlation. However, the TiC based material was considerably less abrasion resistant with a wear loss about x10 higher than WC based materials of the same hardness.

For property mapping the Hall-Petch correlation between H and d was used to derive the expression relating Abrasion resistance (volume loss), A , to d , since

$$\log A = g + hH$$

where g and h are constants, A is in cm^3 and H is the HV30 value.

$$\text{but} \quad H = e + fd^{-0.5}$$

$$\text{thus} \quad \log A = i + kd^{-0.5} \quad (5)$$

where i and k are constants, and d is in μm .

The abrasion resistance measurements for the CAM3/4/9 materials are shown plotted against grain size in Fig 64 and inverse square root of the grain size in Fig 65 with the abrasion resistance (volume loss) plotted on a logarithmic scale. Analysis of the data in Figs 54, 64 and 65 allowed an expression to be written for the variation of abrasion resistance, A , with grain size, d , for $6 < \text{Co} < 25 \text{ wt\%}$ as follows:

$$\log_{10} A = (0.19 - 0.016 * \% \text{ Co}) - \frac{(2.075 - 0.133 * \% \text{ Co} + 0.0022 * (\% \text{ Co})^2)}{\sqrt{d}} \quad (6)$$

Expression (6) can be plotted as a property map, Figs 66 and 67; in Fig 66 with x as $d^{-0.5}$ and in Fig 67 with x as d .

A property map using $\text{Co wt\%}$ content as the variable can also be plotted from expression (6): This is shown in Fig 68 for different values of the WC linear intercept grain size.

4.1.4 Palmqvist Toughness

Toughness can be related to the Co mean free path [3]. The Co mean free path is linearly related to WC grain size for materials with conventional WC grain size distributions [4]. Therefore the following expression was used to evaluate the Palmqvist toughness results for property mapping:

$$T = m + nd \quad (7)$$

where m and n are constants.

The Palmqvist toughness values, expressed in units of $\text{MN m}^{-3/2}$, for the CAM3/4 materials are plotted in Fig 69.

Analysis of these data for the 6, 10 and 15% Co hardmetals allowed an expression to be written for the variation in Palmqvist toughness with grain size as a property map:

$$T = 8.8 + (10^{(-0.33 + 0.088 * \% \text{ Co})}) * d \quad (8)$$

Expression (8) is plotted as a property map in Fig 70. The property map was derived only for the 6-15% Co hardmetals due to the small numbers of results for the higher Co content materials and the greater uncertainty associated with these measurements arising from the difficulty of generating Palmqvist cracks in these higher Co hardmetals.

A property map using $\text{Co wt\%}$ content as the variable can also be plotted from expression (8): This is shown in Fig 71 for different values of the WC linear intercept grain size.

4.2 COMPARATIVE PROPERTY MAPS

The expressions developed in section 4.1 for the Microstructure Property Maps were used to derive the following comparative property maps.

$$\begin{array}{cc} K & v & H \\ A & v & H \end{array} \qquad \begin{array}{cc} T & v & H \\ A & v & T \end{array}$$

Other combinations are possible, but these were selected as examples because hardness is used industrially quite frequently as the property with which other properties are compared. Also the maps are plotted for different representative Co contents. Equally maps can be drawn for different WC grain sizes.

The first comparative map was derived for the relation between coercivity and hardness. Fig 72 shows the baseline data that was used to derive the expressions in section 4.1 also plotted as coercivity against hardness for comparison. Fig 73 shows the calculated property map. More results for the finer WC grain sizes would help in confirming the extrapolations required to generate the plots for the map at higher Co contents.

The second comparative map, Fig 74, shows the relation between Palmqvist toughness and hardness. The concurrence of the plots for different Co contents agrees well with the measured data (Fig 55) and confirms the general accuracy of the map within the boundaries of the current measurements.

The third comparative map, Fig 75, shows the relation between Abrasion (vol loss) and hardness. The form of this map is similar to that in Fig 54 showing the measured data but there is more scatter than in the set comparing Palmqvist toughness with hardness. More work is probably required to derive accurate values for the coefficients in the expression relation Abrasion (vol loss) to grain size, particularly for the coarse grain size high Co materials.

The fourth comparative map, Fig 76, shows the relation between Abrasion (vol loss) and Palmqvist toughness. Again the lack of a variation with changing cobalt content agrees well with the conclusions of the other maps described above. There is an equal correspondence between the properties, and changing either Co content or grain size does not show significant deviation from the overall trend. There is some uncertainty at the high toughness values however due to the difficulty in making accurate measurements of toughness at values greater than about $20 \text{ MNm}^{-3/2}$.

5 SUMMARY

Over 30 hardmetals have been characterised in work at NPL and through industrial contributions for:

Composition	Industry
WC grain size and distribution	NPL
Coercivity	Industry
Magnetic moment	NPL/Industry
Density	NPL/Industry
Hardness	NPL/Industry
Abrasion resistance (ASTM B611)	NPL
Palmqvist toughness	NPL

The majority of the hardmetals were based on WC/Co but a few contained Ni or Co/Ni as a binder-phase and one was manufactured using TiC/Mo₂C rather than WC.

The results of the measurements combined with data from previous work on 6 and 10% Co hardmetals form a baseline data set that can be used to evaluate new materials or to benchmark current products for quality and consistency.

The results of the tests were used to derive 12 Property Maps, eight based on microstructure and four based on property comparison. These comprised:

WC Grain Size - Microstructure:

Coercivity; Hardness; Abrasion; Palmqvist toughness

Co Content - Microstructure:

Coercivity; Hardness; Abrasion; Palmqvist toughness

Comparative Maps:

Coercivity/Hardness

Palmqvist toughness/Hardness

Abrasion/Hardness

Abrasion/Palmqvist toughness

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

6 REFERENCES

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4. B Roebuck and E G Bennett. Phase Size Distribution in WC/Co Hardmetals, Metallography, 1986, 19, No 1, 27-77.

7 ACKNOWLEDGEMENTS

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LIST OF CAPTIONS

Density measurements

Magnetic moment measurements

Coercivity measurements

SEM and optical micrographs of MA6

SEM and optical micrographs of MA10

Fig 6 SEM and optical micrographs of MA15

SEM and optical micrographs of MA20

SEM and optical micrographs of MA24

SEM and optical micrographs of MAN6

Fig 10 SEM and optical micrographs of MAN10

Fig 11 SEM and optical micrographs of CWC15F

Fig 12 SEM and optical micrographs of CWC15C

Fig 13 SEM and optical micrographs of CWC20C

Fig 14 SEM and optical micrographs of CWC25C

Fig 15 SEM and optical micrographs of CWN8

Fig 16 SEM and optical micrographs of T

Fig 17 SEM and optical micrographs of UC9

Fig 18 SEM and optical micrographs of M15

Fig 19 SEM and optical micrographs of T6

Fig 20 SEM and optical micrographs of G10

Fig 21 SEM and optical micrographs of G15

Fig 22 SEM and optical micrographs of N6

Fig 23 SEM and optical micrographs of N10

Fig 24 SEM and optical micrographs of N15

Fig 25 SEM and optical micrographs of TC6

Fig 26 SEM and optical micrographs of T16D

Fig 27 SEM and optical micrographs of T20D

Fig 28 SEM and optical micrographs of T25D

Fig 29 SEM and optical micrographs of SHM5CN

Fig 30 SEM and optical micrographs of SHMUF

Fig 31 High magnification SEM micrographs of SHM5CN and SHMUF

Fig 32 SEM and optical micrographs of D10

Fig 33 SEM and optical micrographs of D15

Fig 34 SEM and optical micrographs of DN6

Fig 35 SEM and optical micrographs of DN10

Fig 36 SEM and optical micrographs of TC222

Fig 37 SEM and optical micrographs of K3560

Fig 38 Cumulative number distribution of intercept data for all the materials

Fig 39 Cumulative number distributions for MA6, MA10, MA15, MA20 and MA24

Fig 40 Cumulative number distributions for MAN6, MAN10, CW15F, CW15C and CW20C

Fig 41 Cumulative number distributions for CW25C, CWN8, T, UC9 and M15

Fig 42 Cumulative number distributions for T6, G10, G15, N6 and N10

Fig 43 Cumulative number distributions for N15, TC6, T16D, T20D and T25D

Fig 44 Cumulative number distributions for SHM5CN, SHMUF, D10, D15 and DN6

Fig 45 Cumulative number distributions for DN10, K3560 and TC222

Fig 46 Size distribution of intercept squared data plotted against normalised intercepts for all the materials

Fig 47 Cumulative size distributions for MA6, MA10, MA15, MA20 and MA24

Fig 48 Cumulative size distributions for MAN6, T6, G10, T16D, DN10 and TC222

Fig 49 Cumulative size distributions for MAN10, CW15C, UC9, N6, N15 and T25D

Fig 50 Cumulative size distributions for CW25C, M15, N10, T20D and K3560

Fig 51 Cumulative size distributions for CW15F, CW20C, CWN8, T, G15 and TC6

Fig 52 Cumulative size distributions for SHM5CN, SHMUF, D10, D15 and DN6

Fig 53 Cumulative size distributions compared with model predictions for a tetrakaidecahedron

Fig 54 Abrasion test results

Fig 55 Palmqvist test results compared with previous data

Fig 56 Coercivity plotted against inverse grain size

Fig 57 Coercivity/inverse grain size property map

Fig 58 Coercivity/grain size property map

Fig 59 Coercivity/Co content property map

Fig 60 Hardness/inverse square root grain size data for CAM3/4 materials

Fig 61 Hardness/inverse square root grain size property map

Fig 62 Hardness/grain size property map

Fig 63 Hardness/Co content property map

Fig 64 Abrasion (volume loss)/grain size data for CAM3/4 materials

Fig 65 Abrasion (volume loss)/inverse square root grain size for CAM3/4 materials

Fig 66 Abrasion (volume loss)/inverse square root grain size property map

Fig 67 Abrasion (volume loss)/grain size property map

Fig 68 Abrasion (volume loss)/Co content property map

Fig 69 Palmqvist toughness data plotted against grain size for the CAM3/4 hardmetals

Fig 70 Palmqvist toughness/grain size property map

Fig 71 Palmqvist toughness/Co content property map

Fig 72 Coercivity/Hardness measurements

Fig 73 Coercivity/Hardness property map

Fig 74 Abrasion (volume loss)/Hardness property map

Fig 75 Toughness (Palmqvist)/Hardness property map

Fig 76 Abrasion (volume loss)/Toughness (Palmqvist) property map

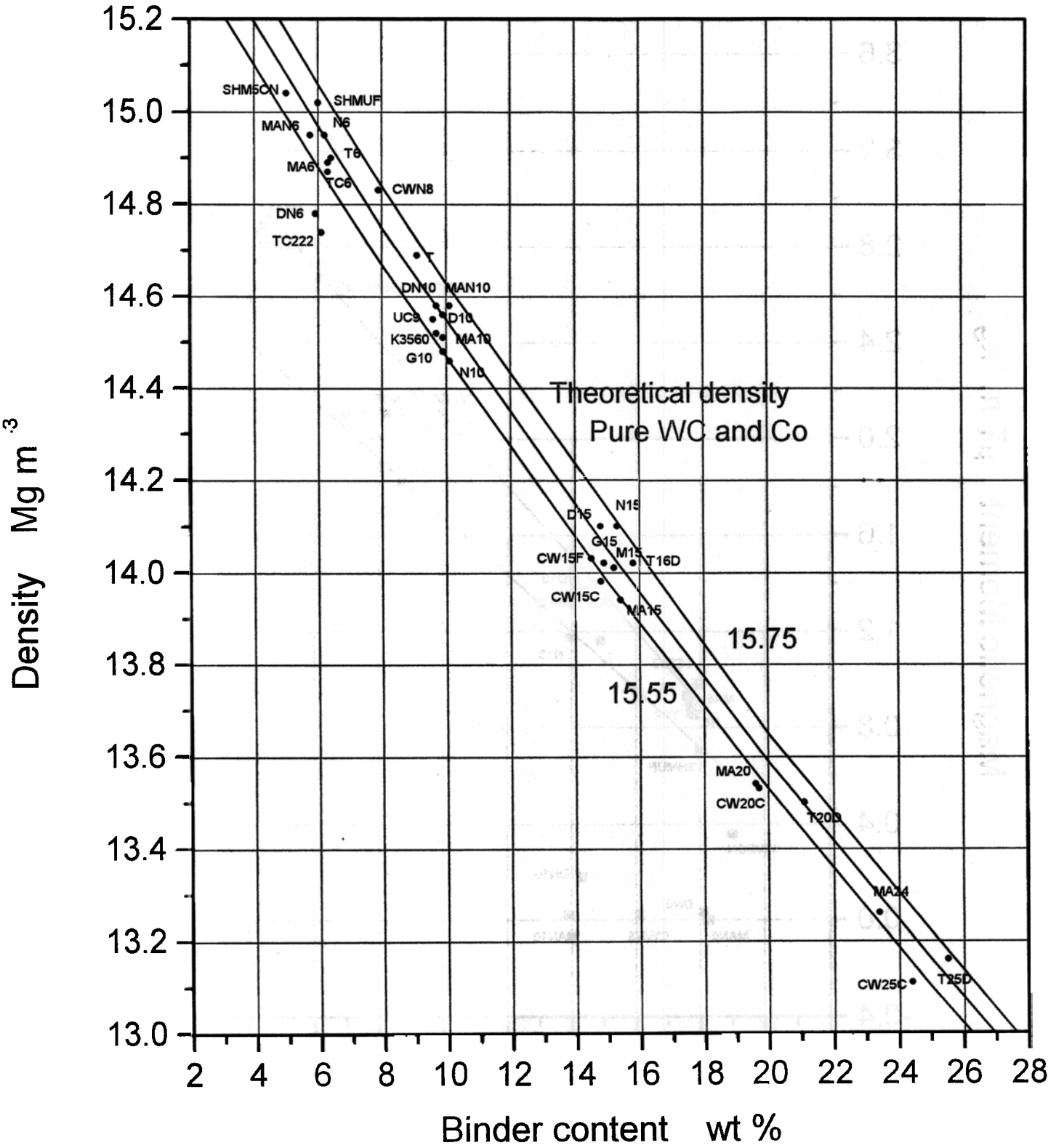


Fig 1 Density measurements

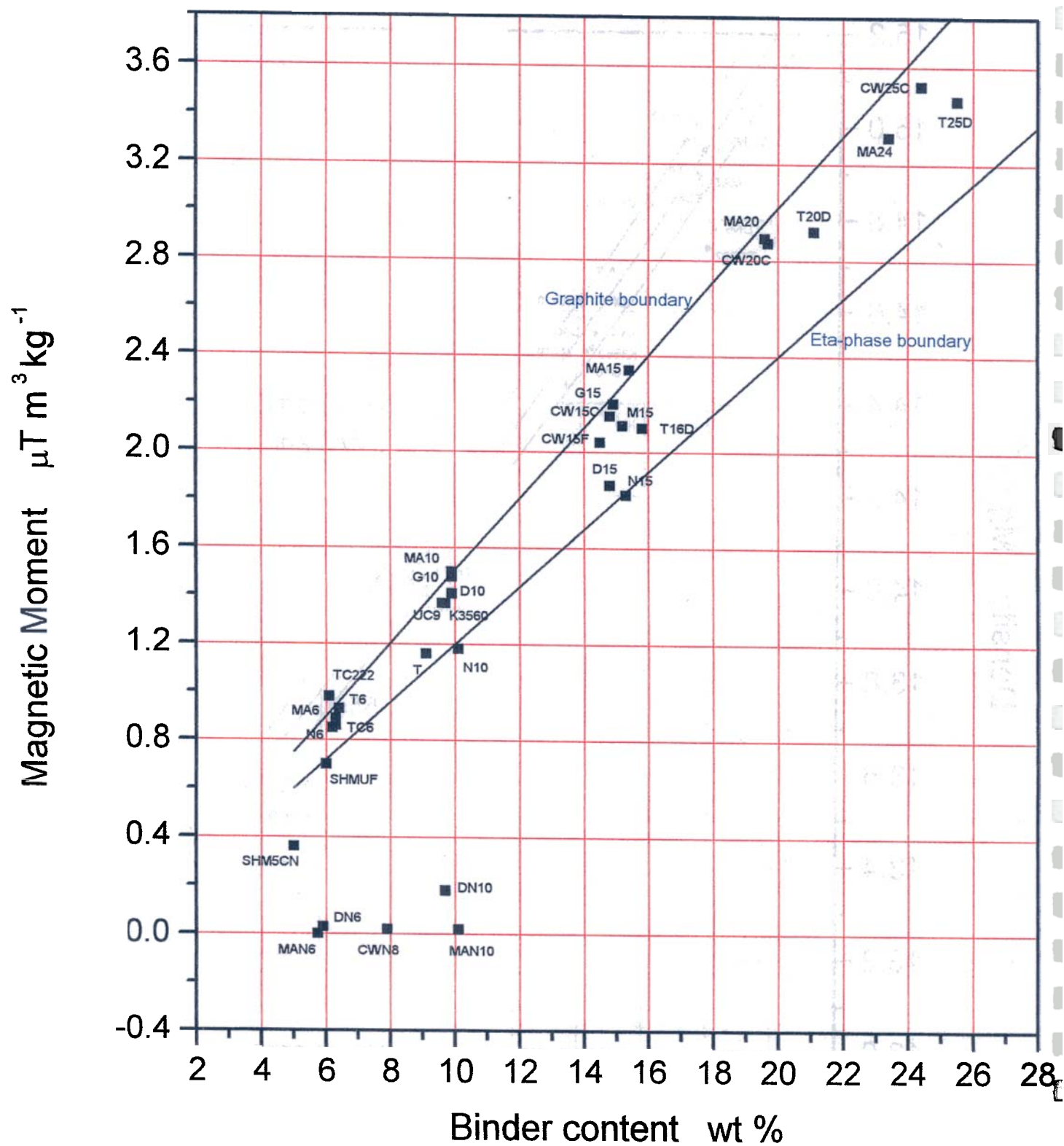


Fig 2 Magnetic moment measurements

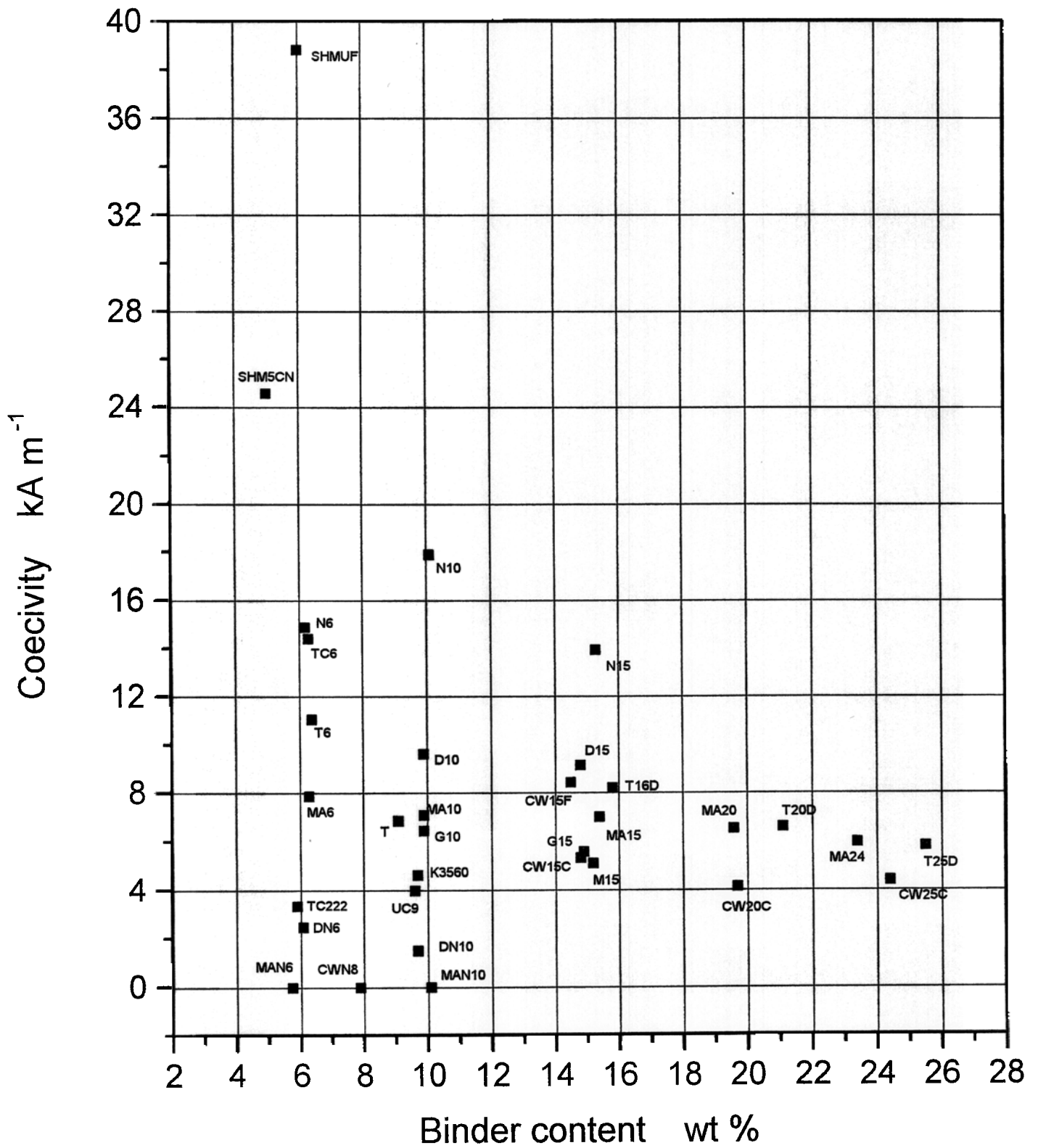


Fig 3 Coercivity measurements

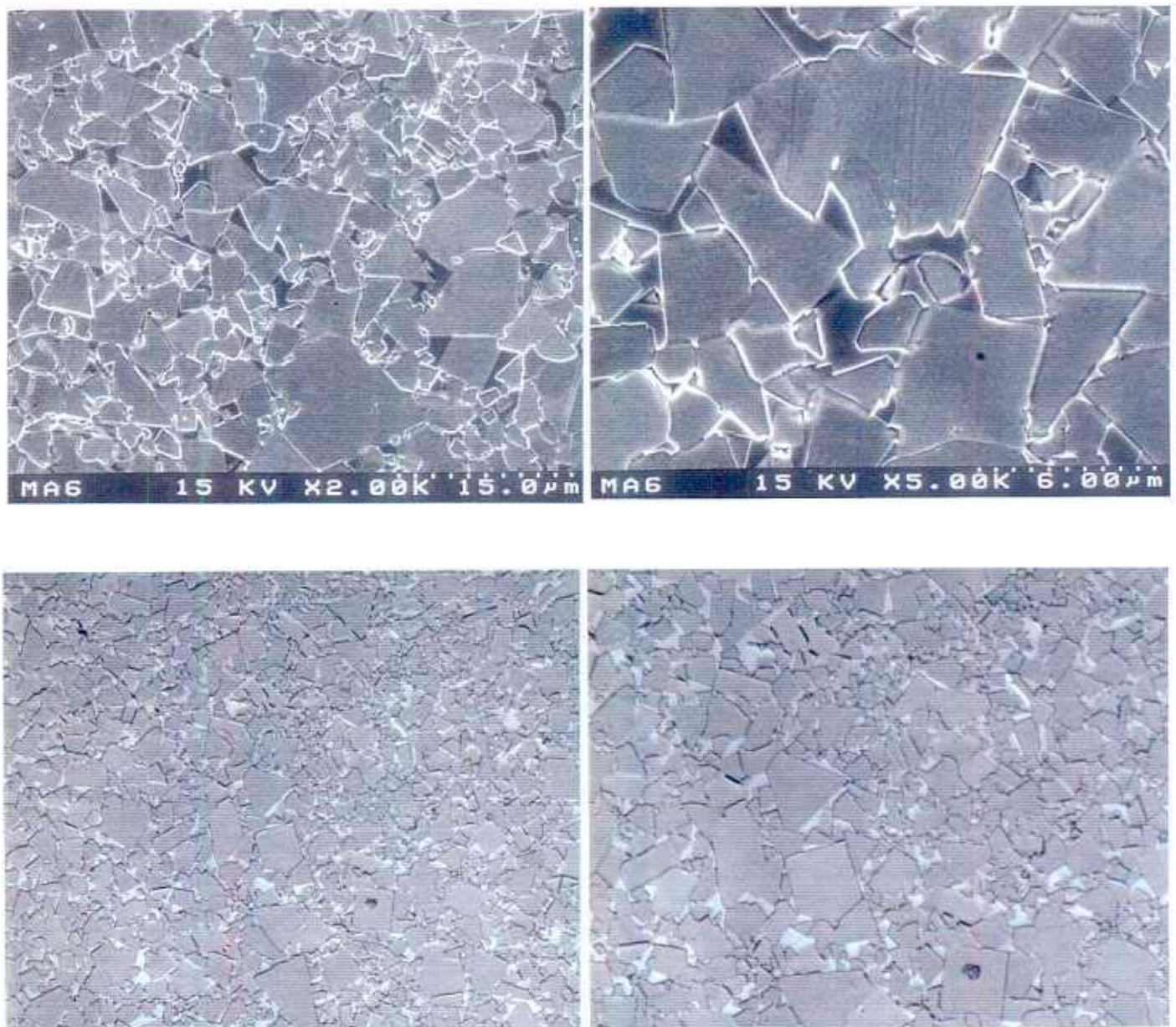


Fig 4 SEM and optical micrographs of MA6

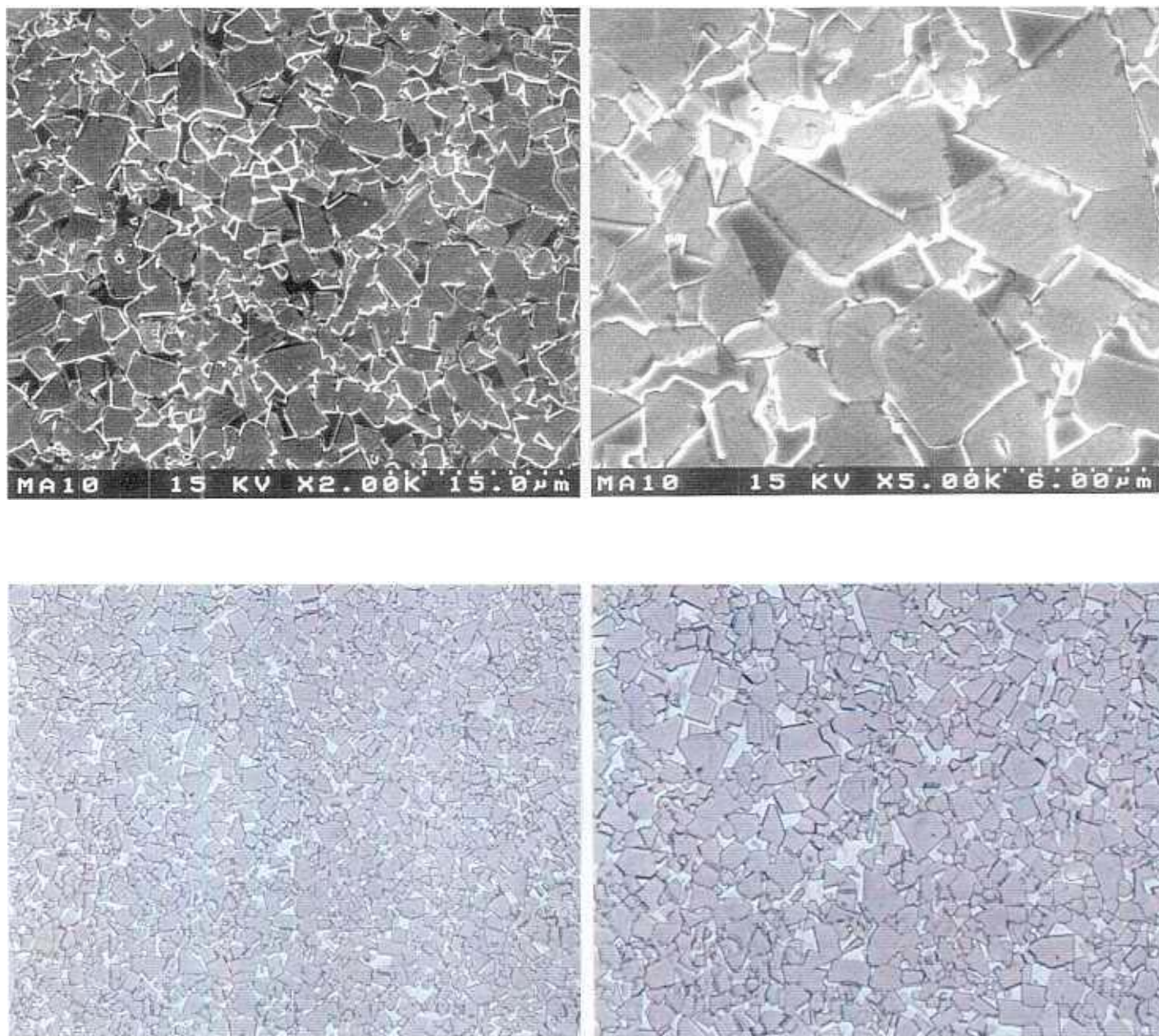


Fig 5 SEM and optical micrographs of MA10

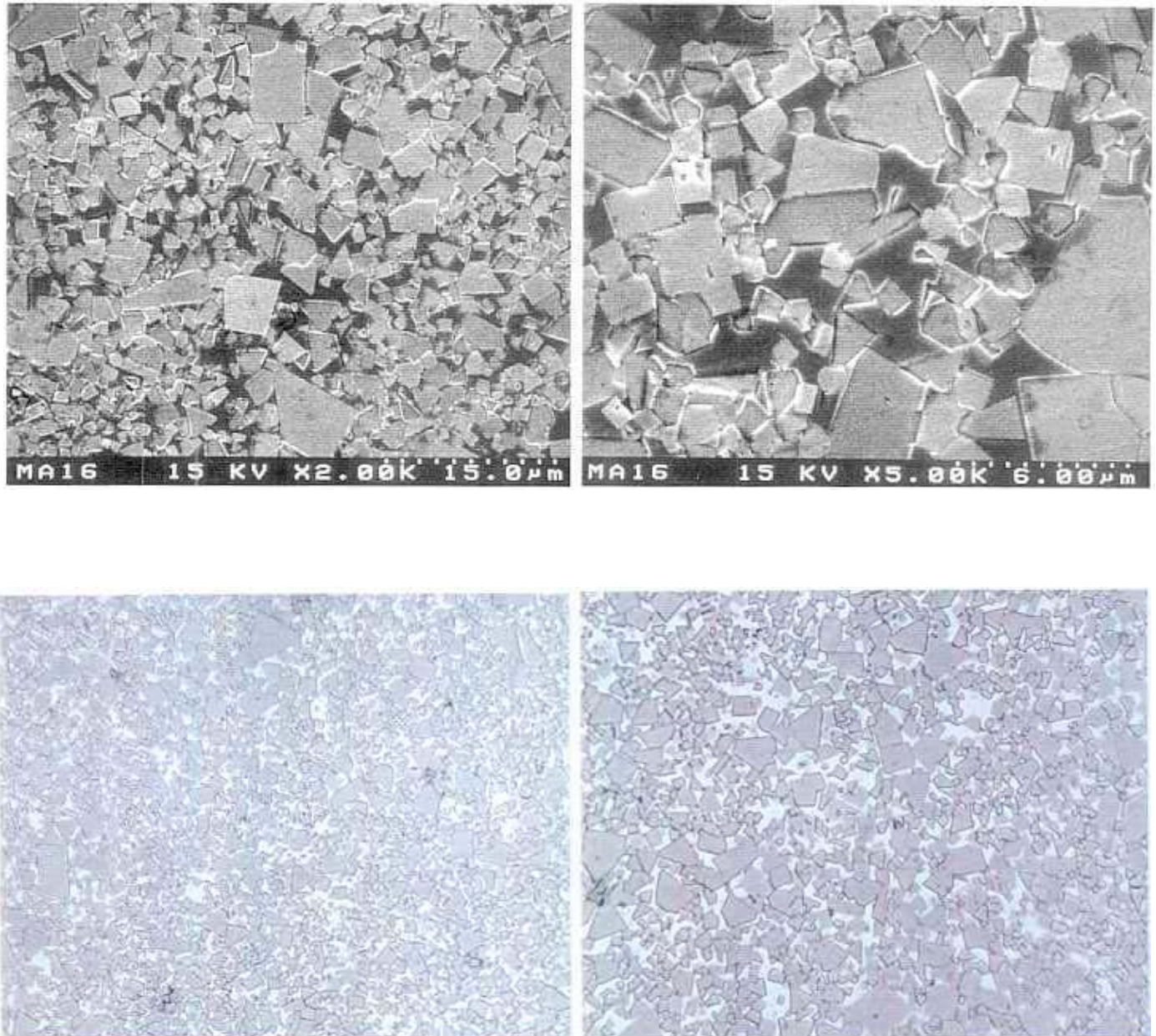


Fig 6 SEM and optical micrographs of MA15

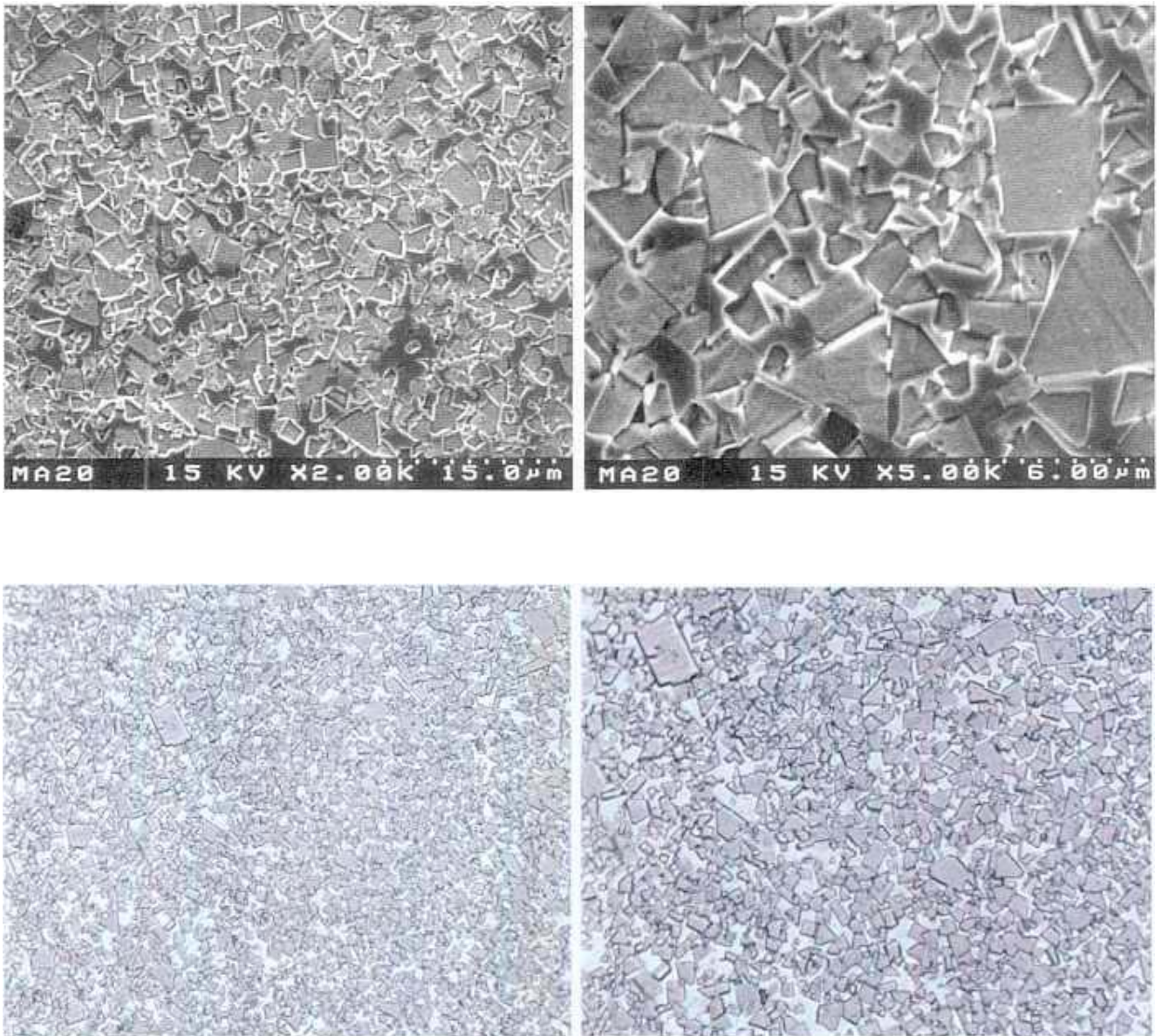


Fig 7 SEM and optical micrographs of MA20

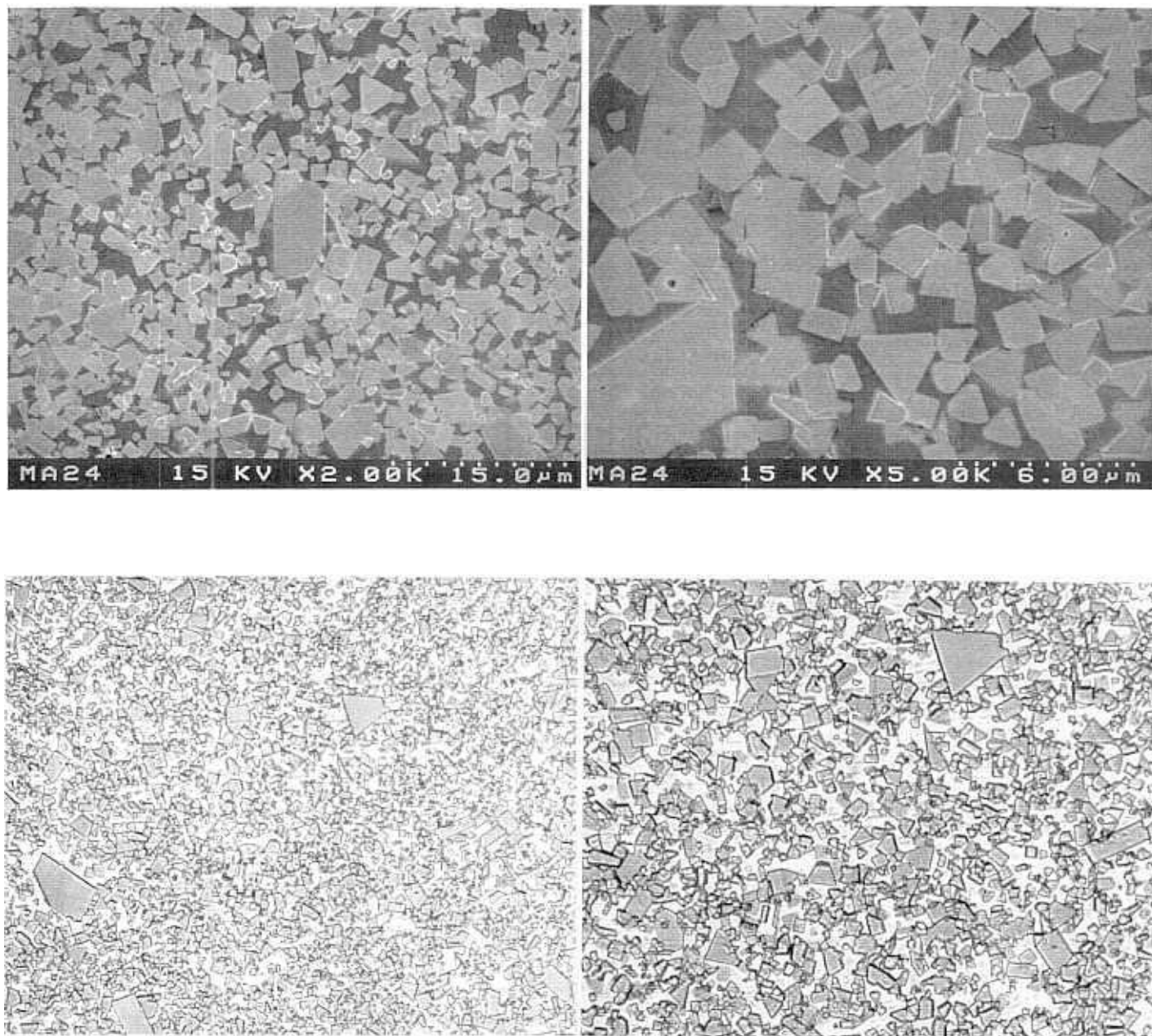


Fig 8 SEM and optical micrographs of MA24

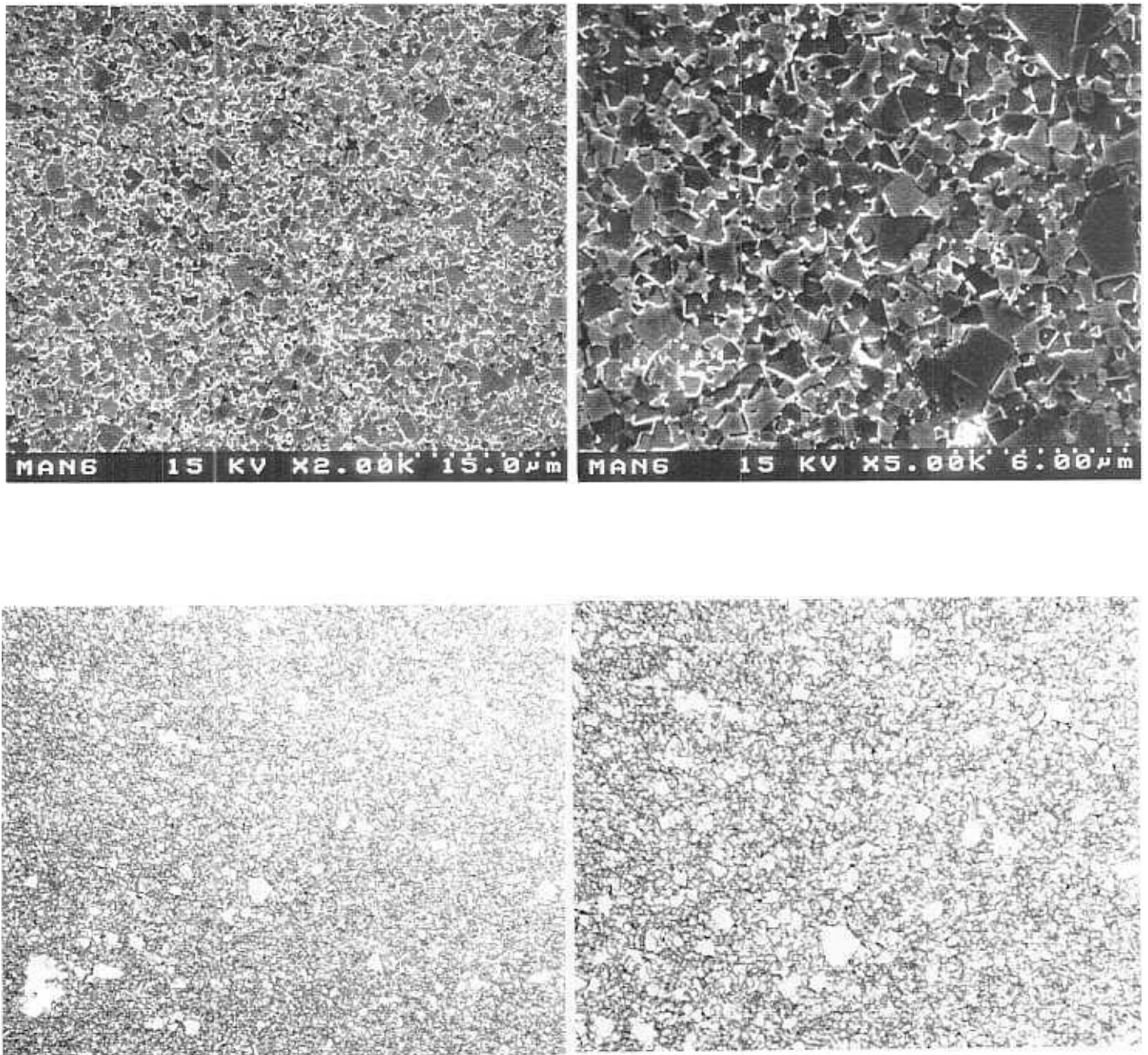


Fig 9 SEM and optical micrographs of MAN6

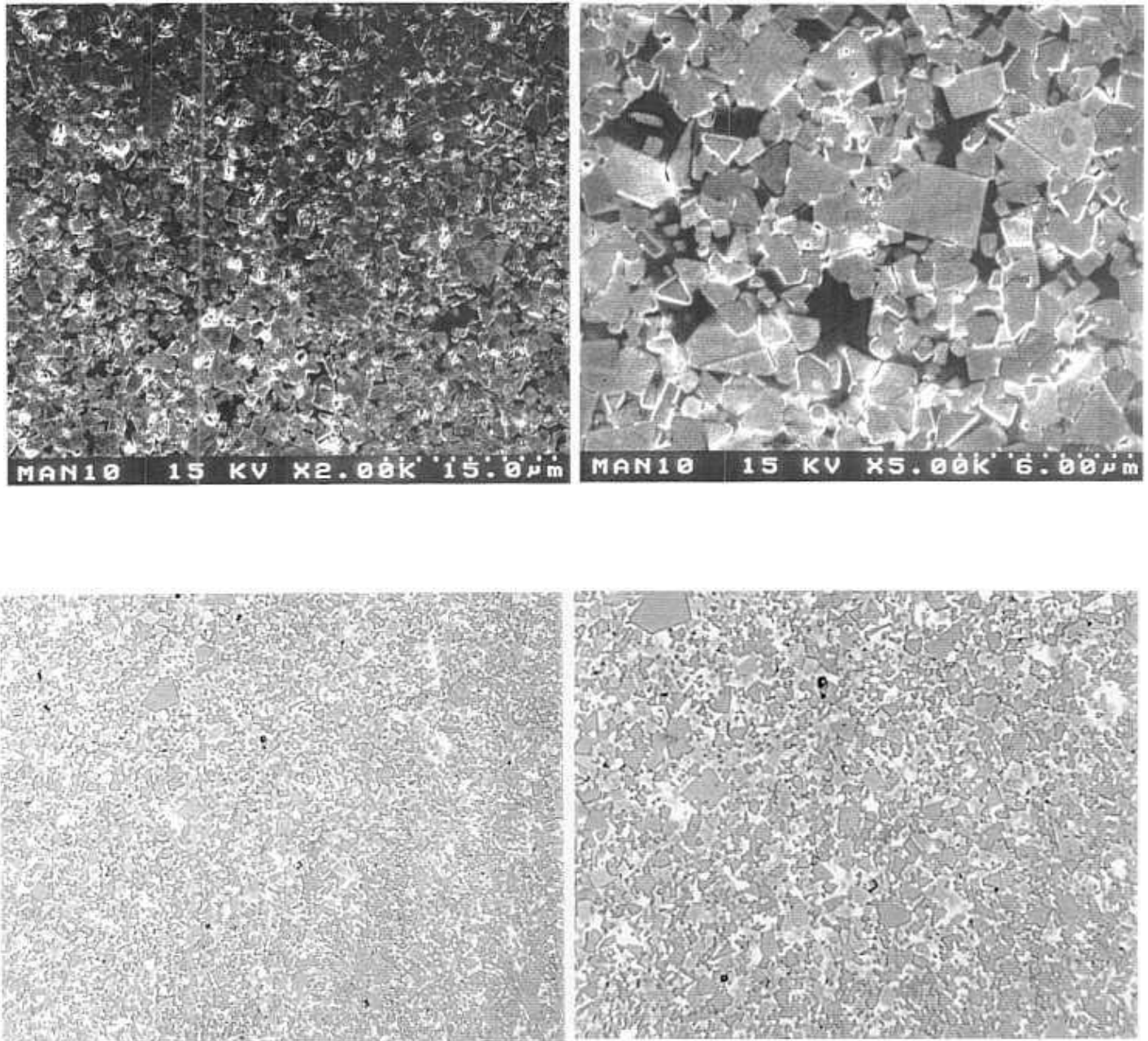


Fig 10 SEM and optical micrographs of MAN10

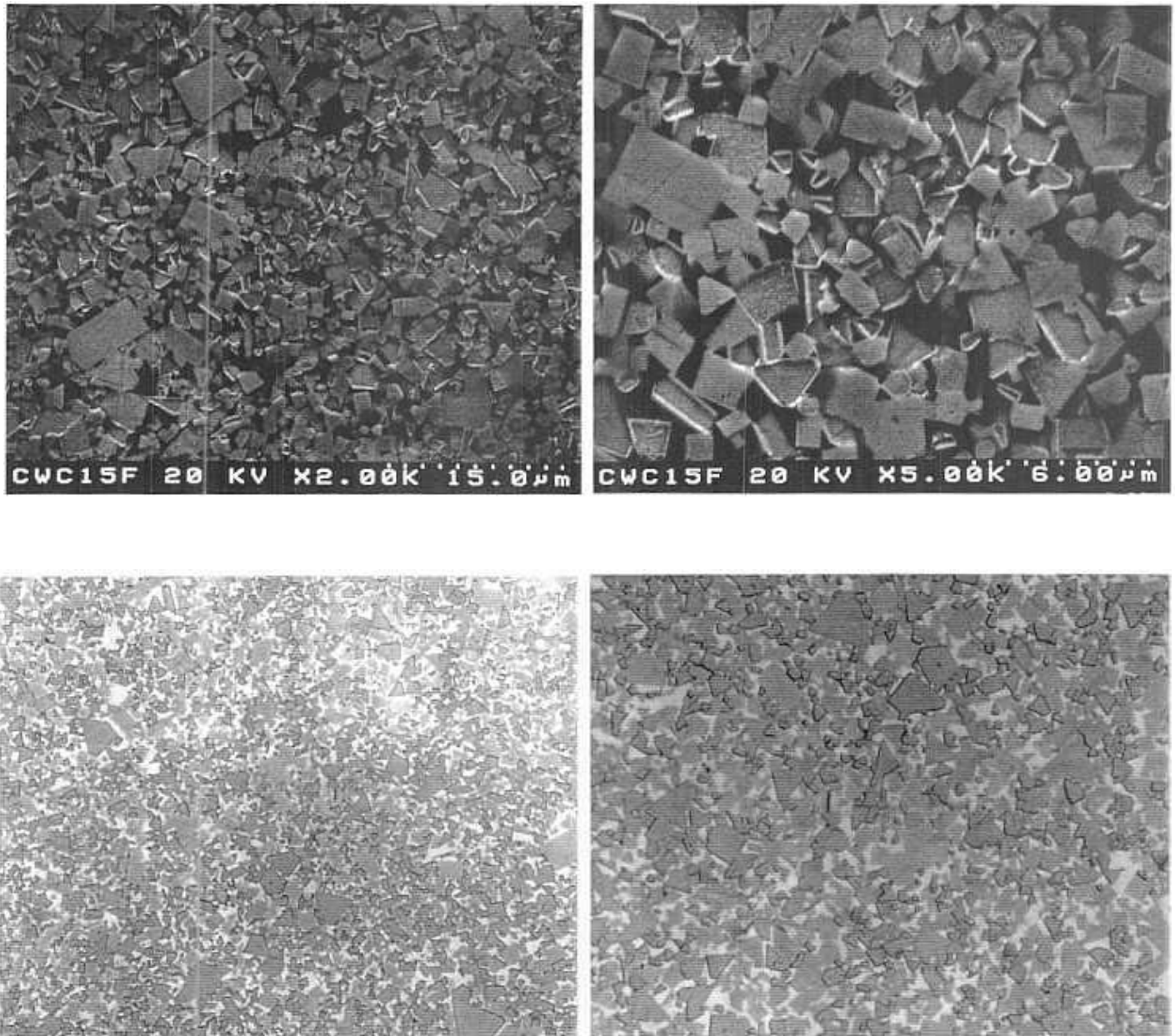


Fig 11 SEM and optical micrographs of CWC15F

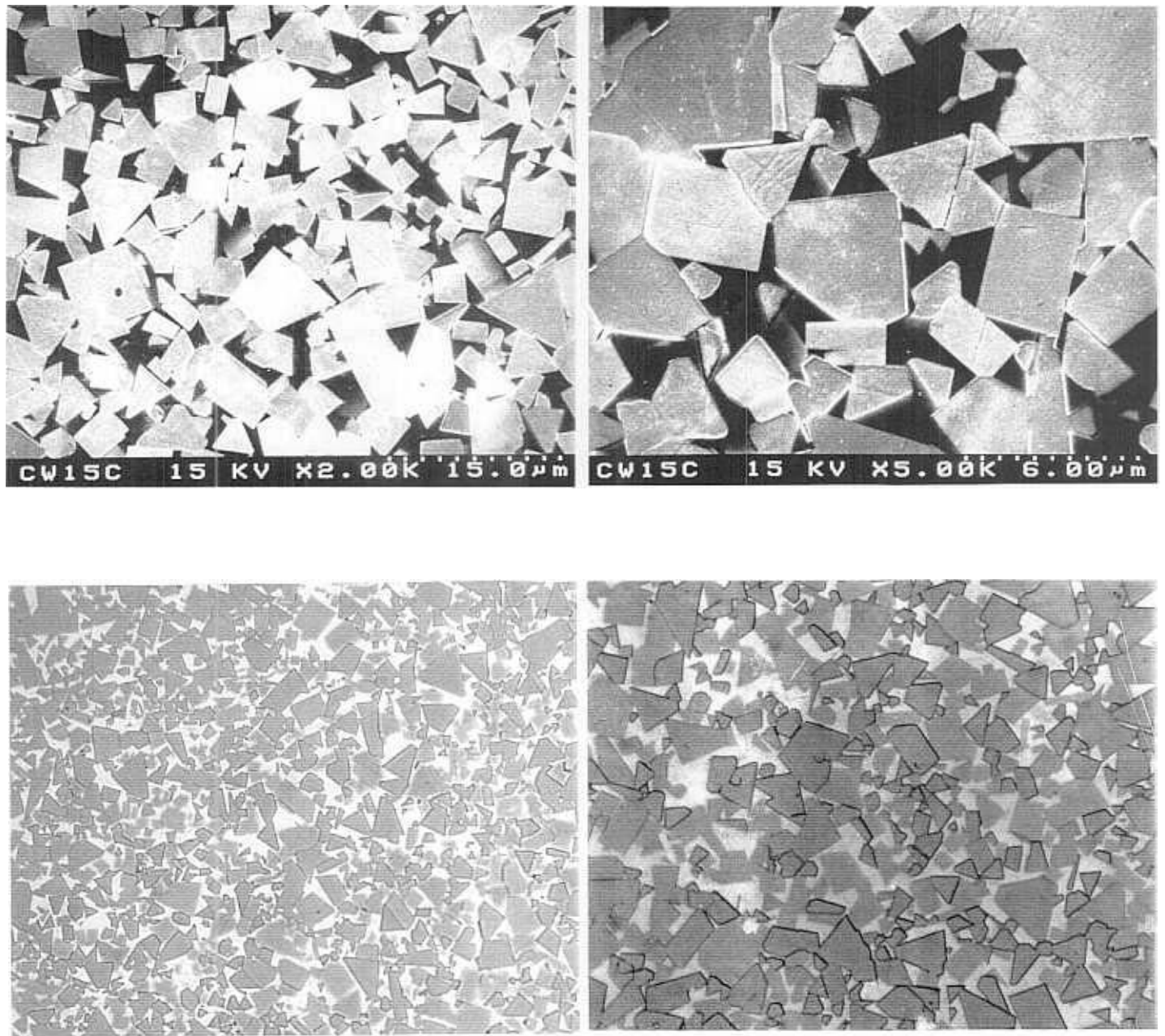


Fig 12 SEM and optical micrographs of CWC15C

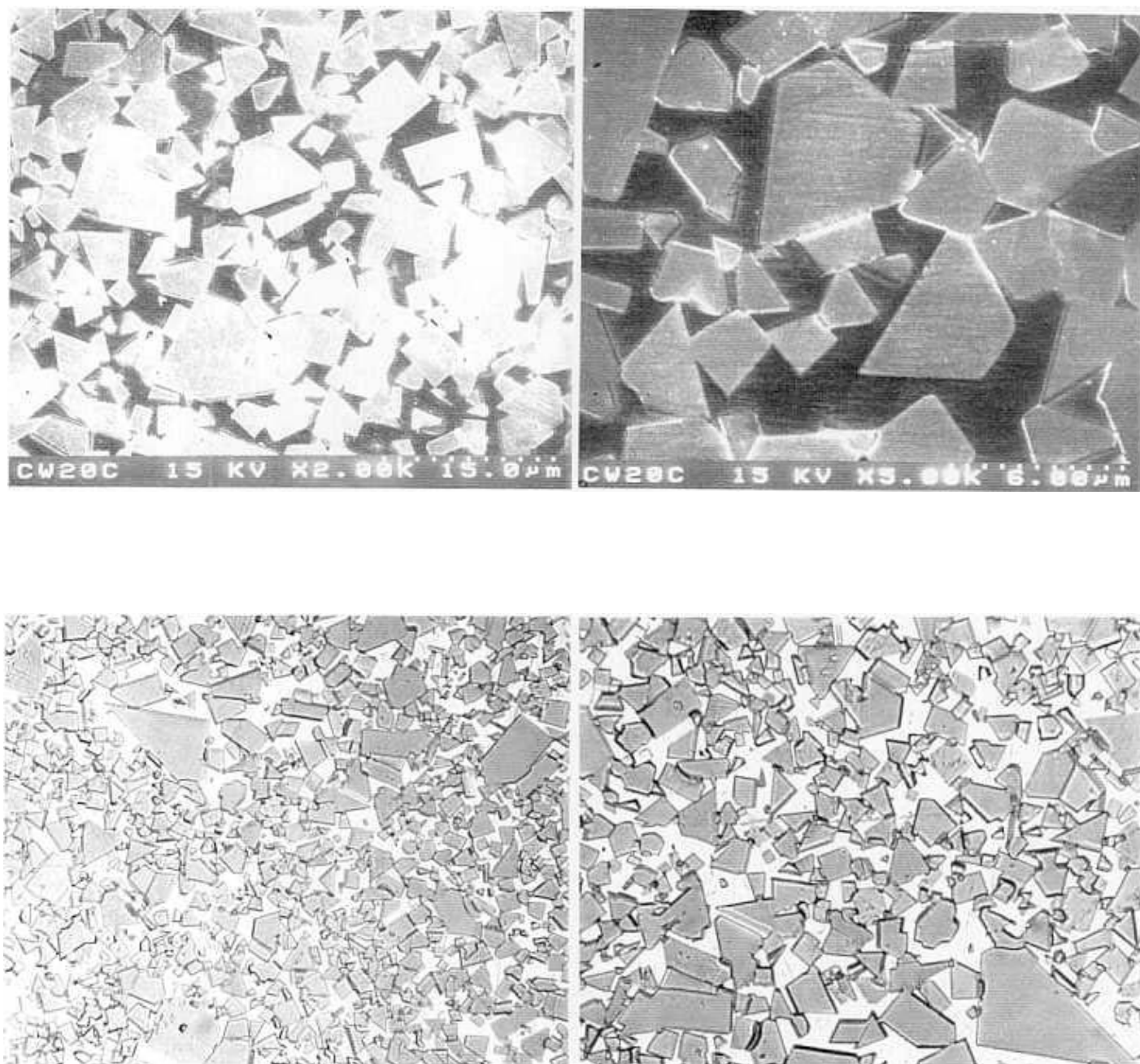


Fig 13 SEM and optical micrographs of CWC20C

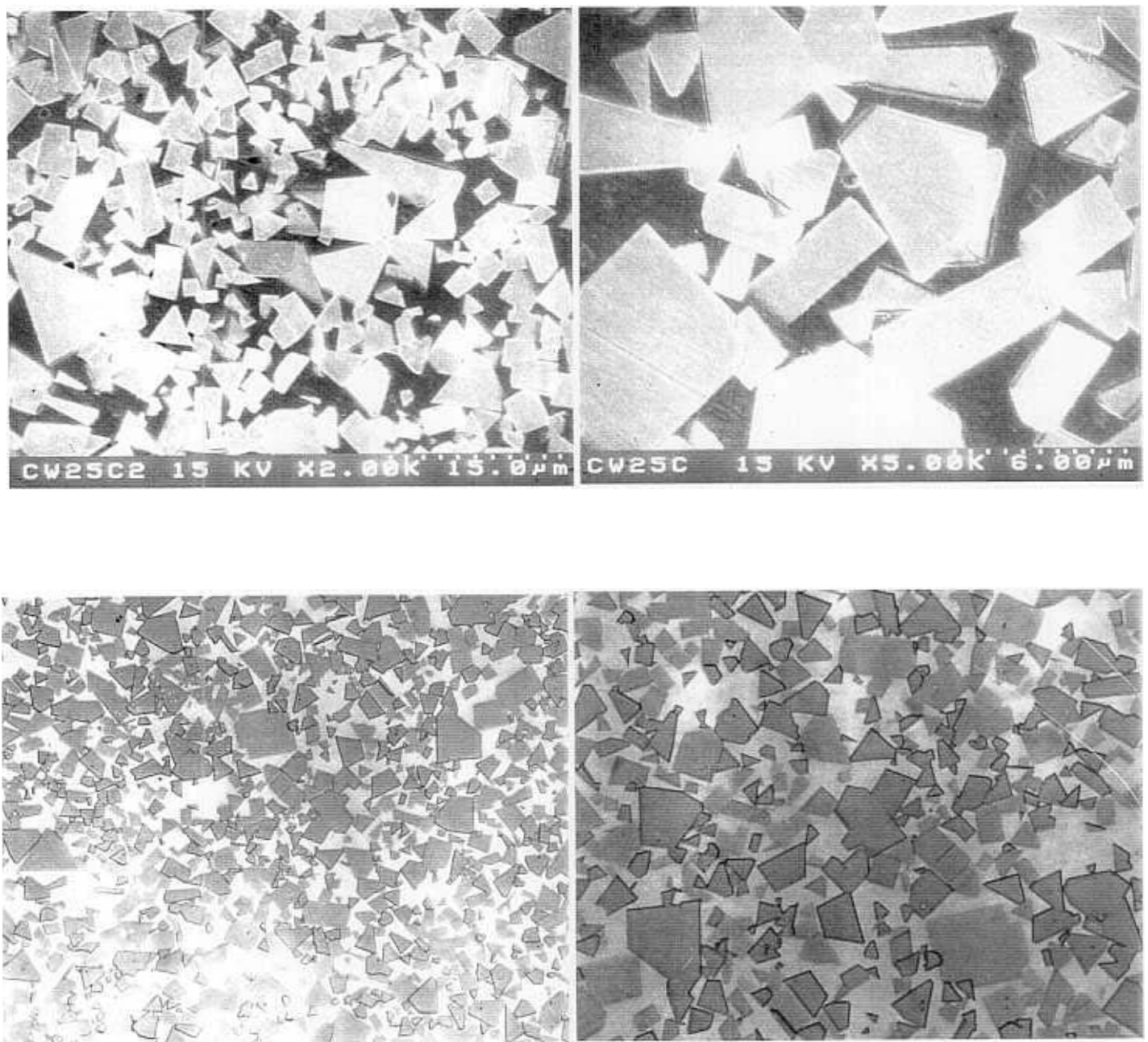


Fig 14 SEM and optical micrographs of CWC25C

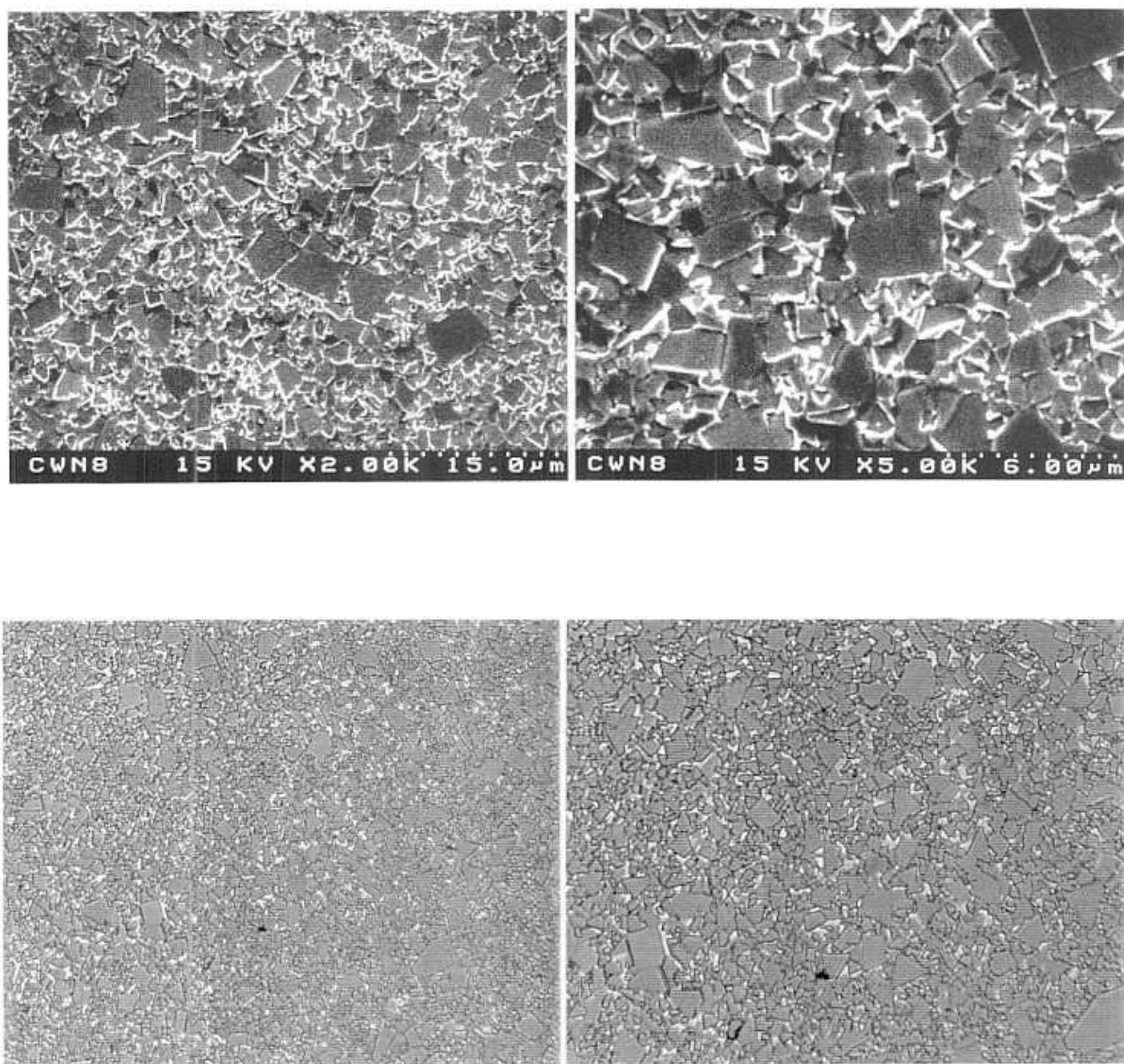


Fig 15 SEM and optical micrographs of CWN8

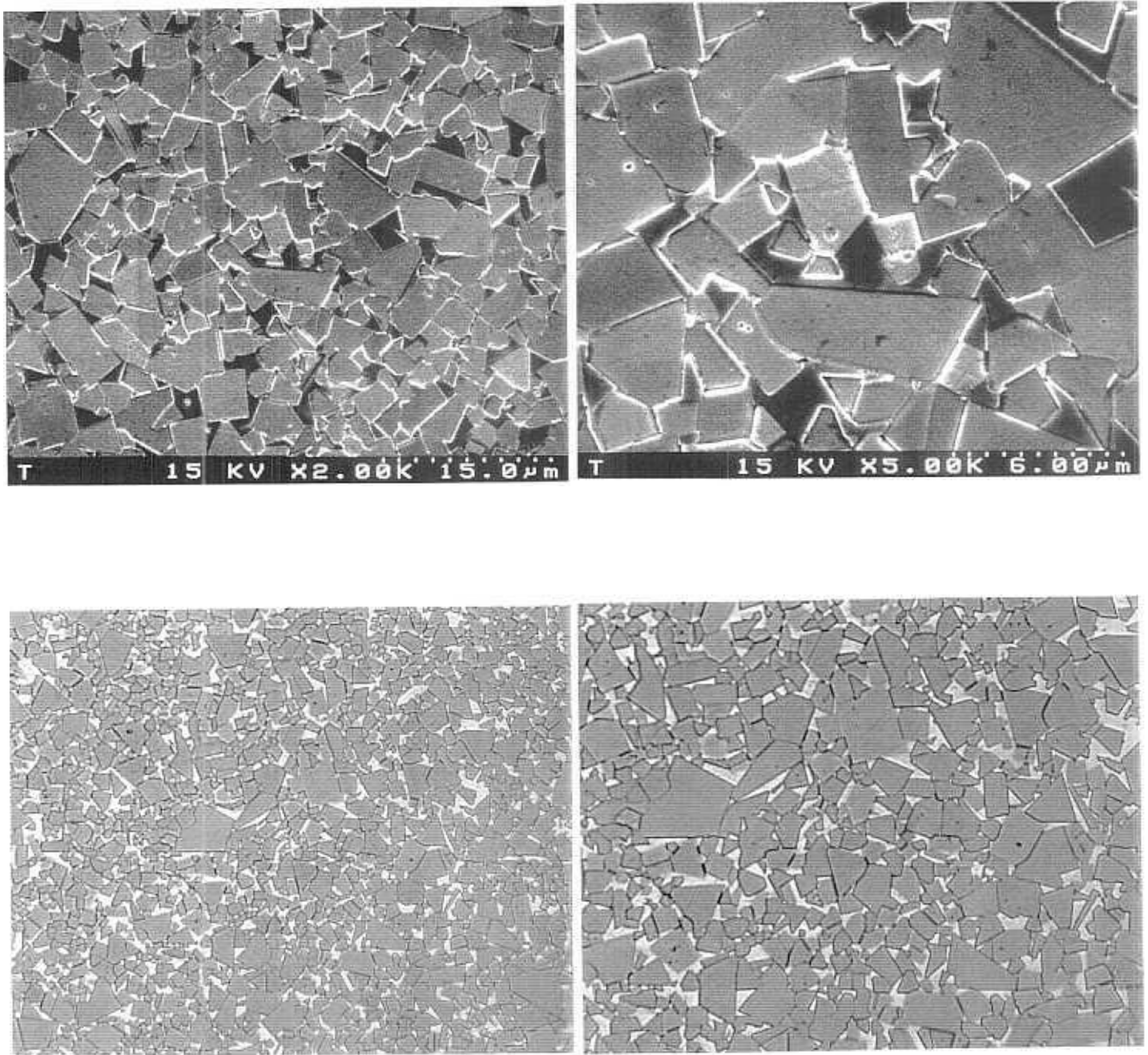


Fig 16 SEM and optical micrographs of T

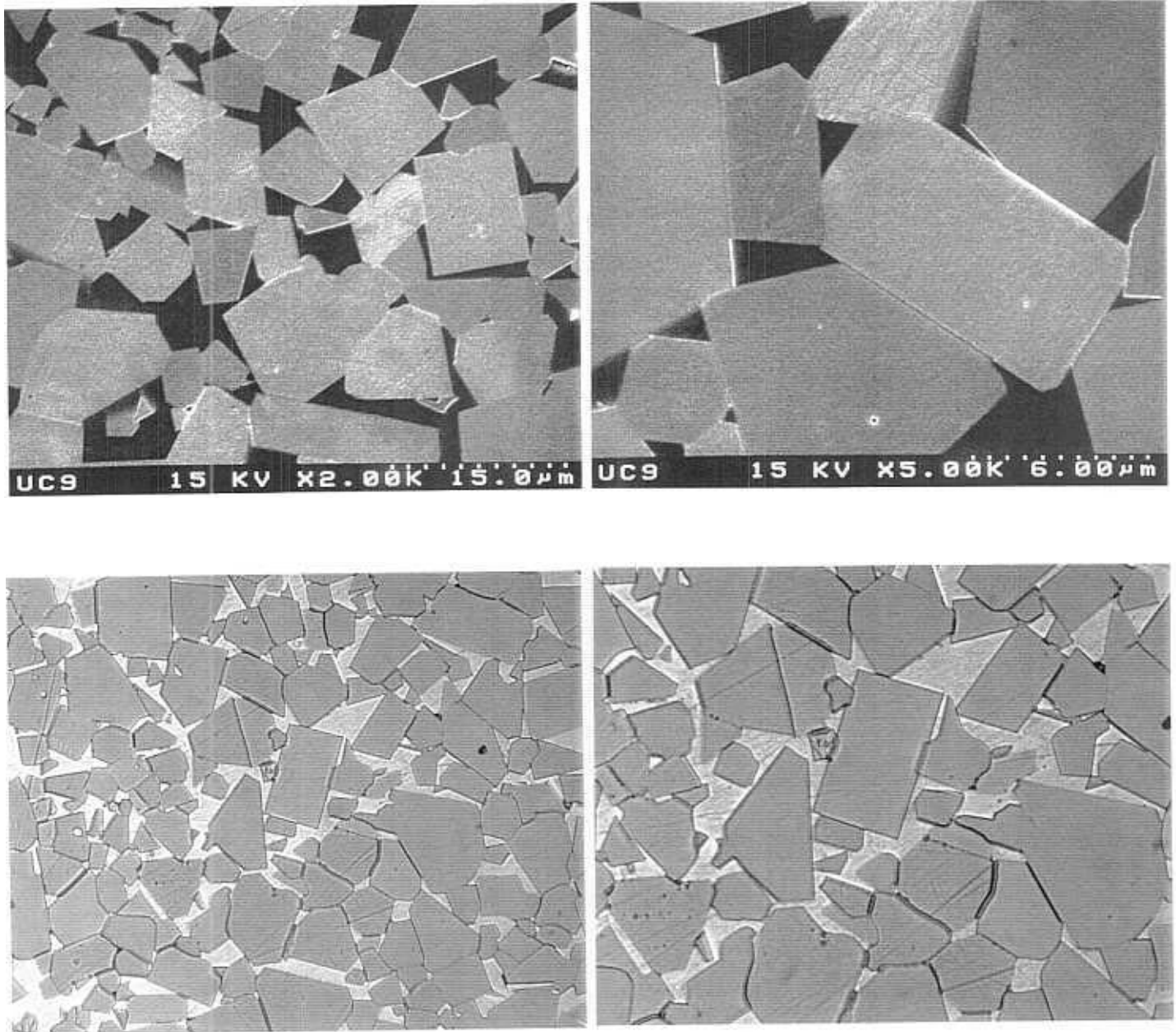


Fig 17 SEM and optical micrographs of UC9

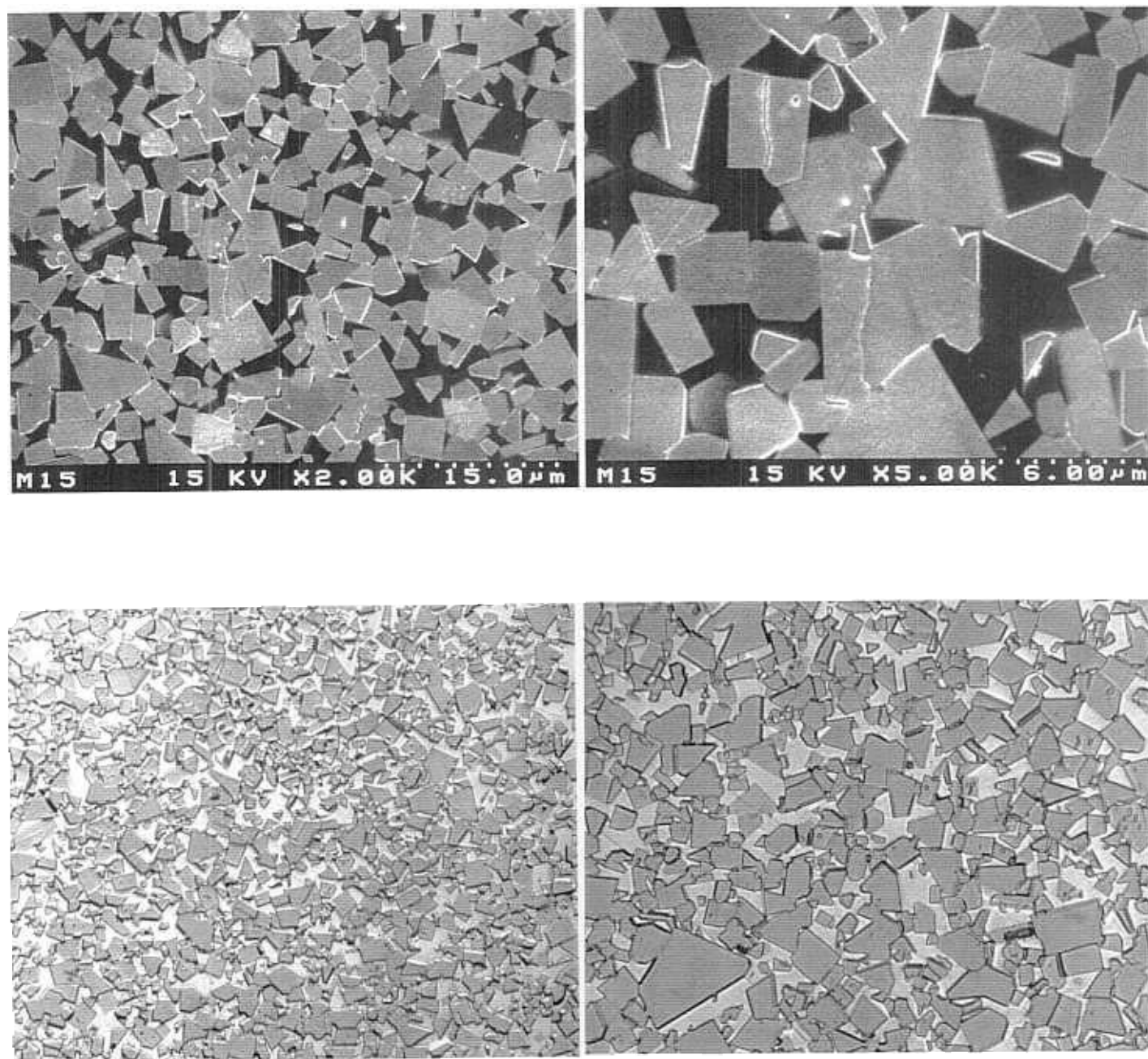


Fig 18 SEM and optical micrographs of M15

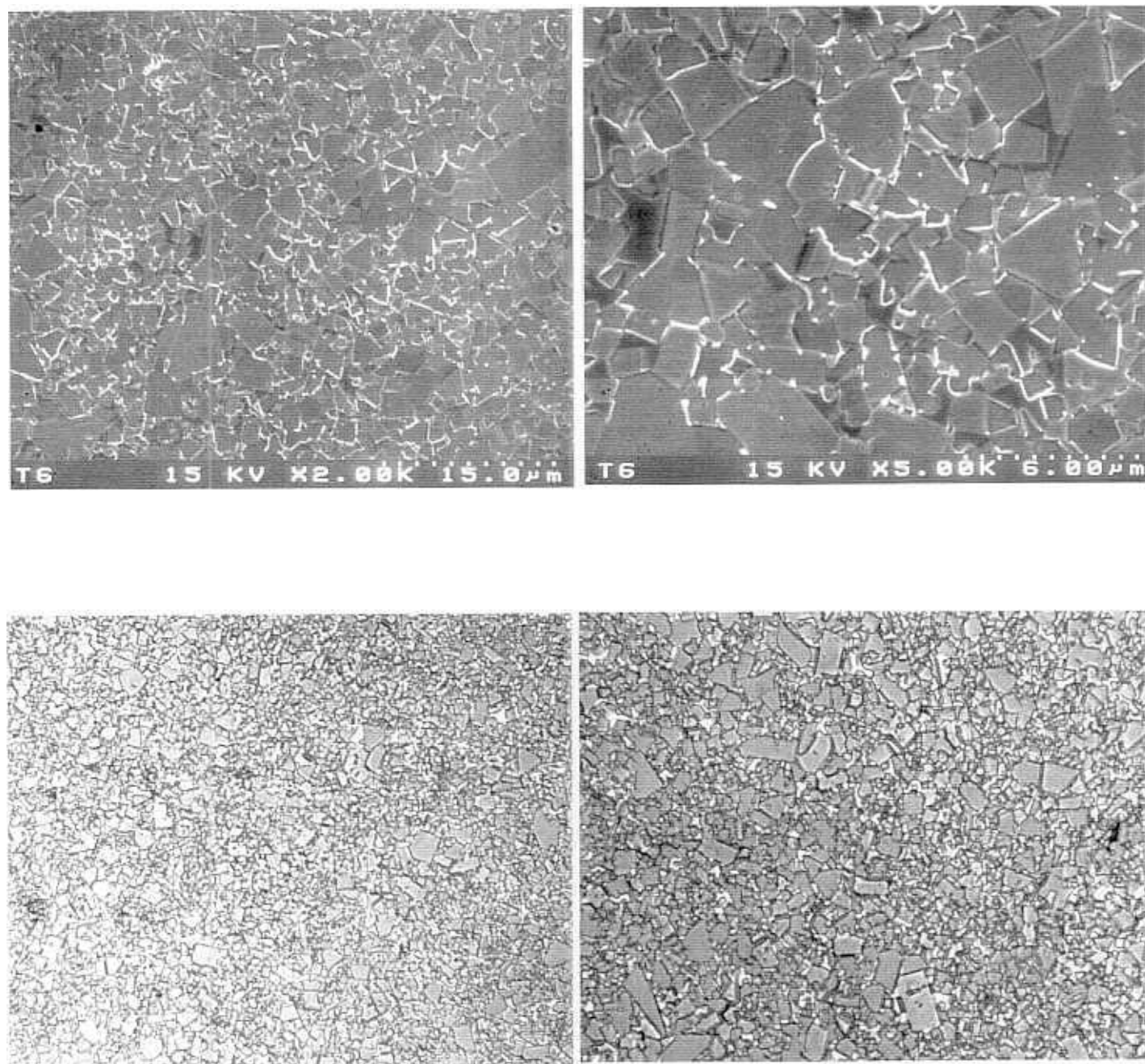


Fig 19 SEM and optical micrographs of T6

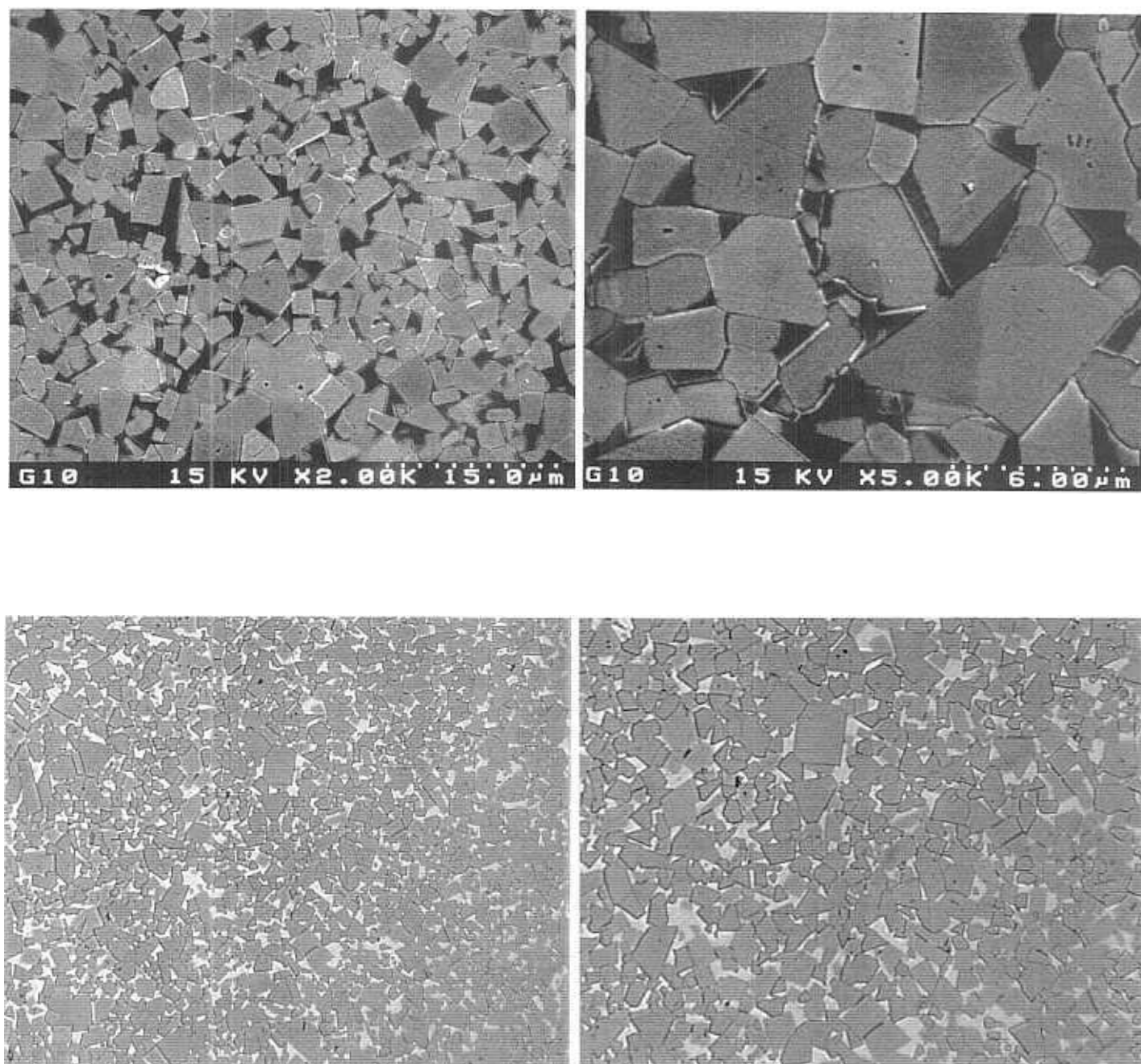


Fig 20 SEM and optical micrographs of G10

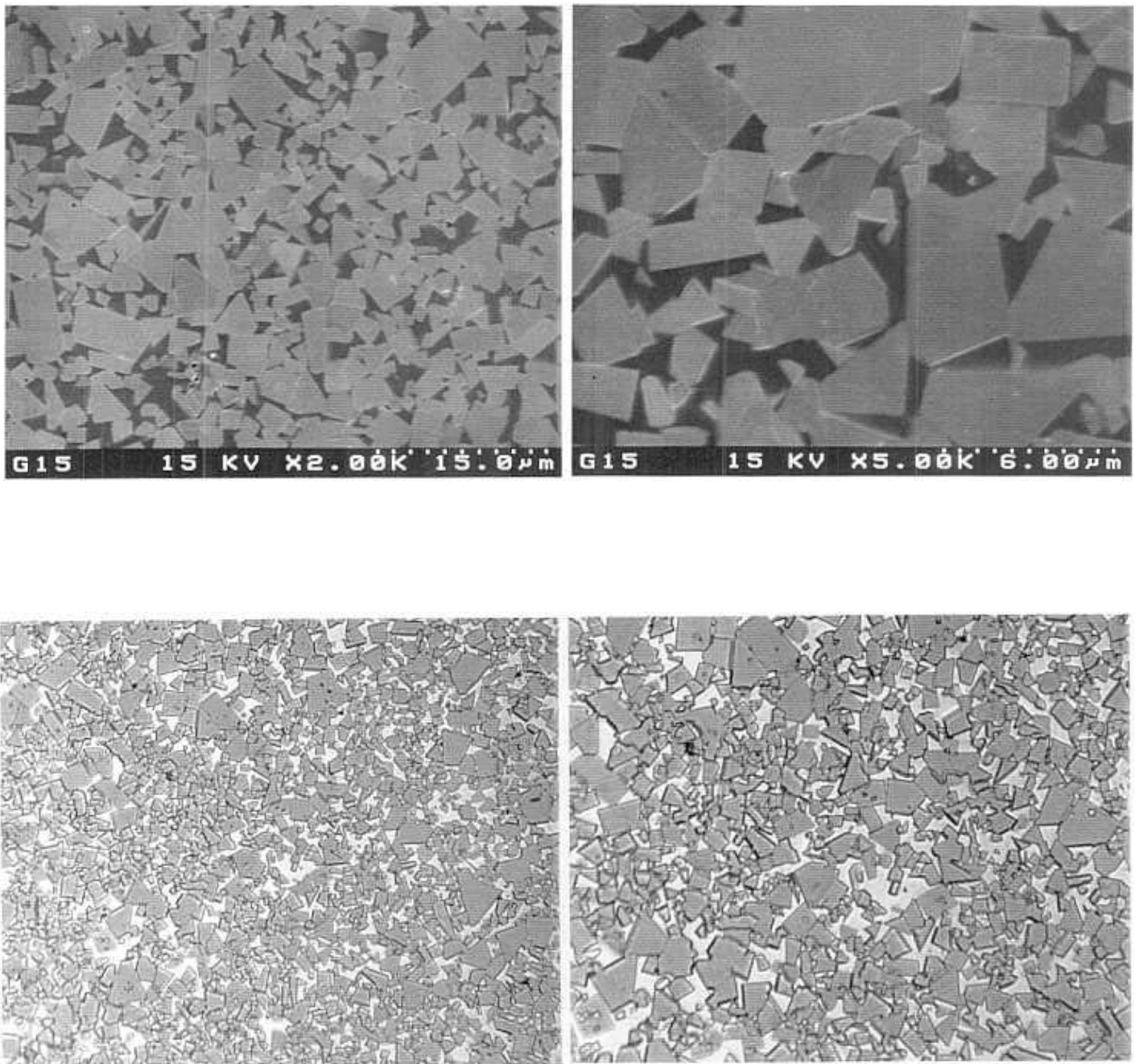


Fig 21 SEM and optical micrographs of G15

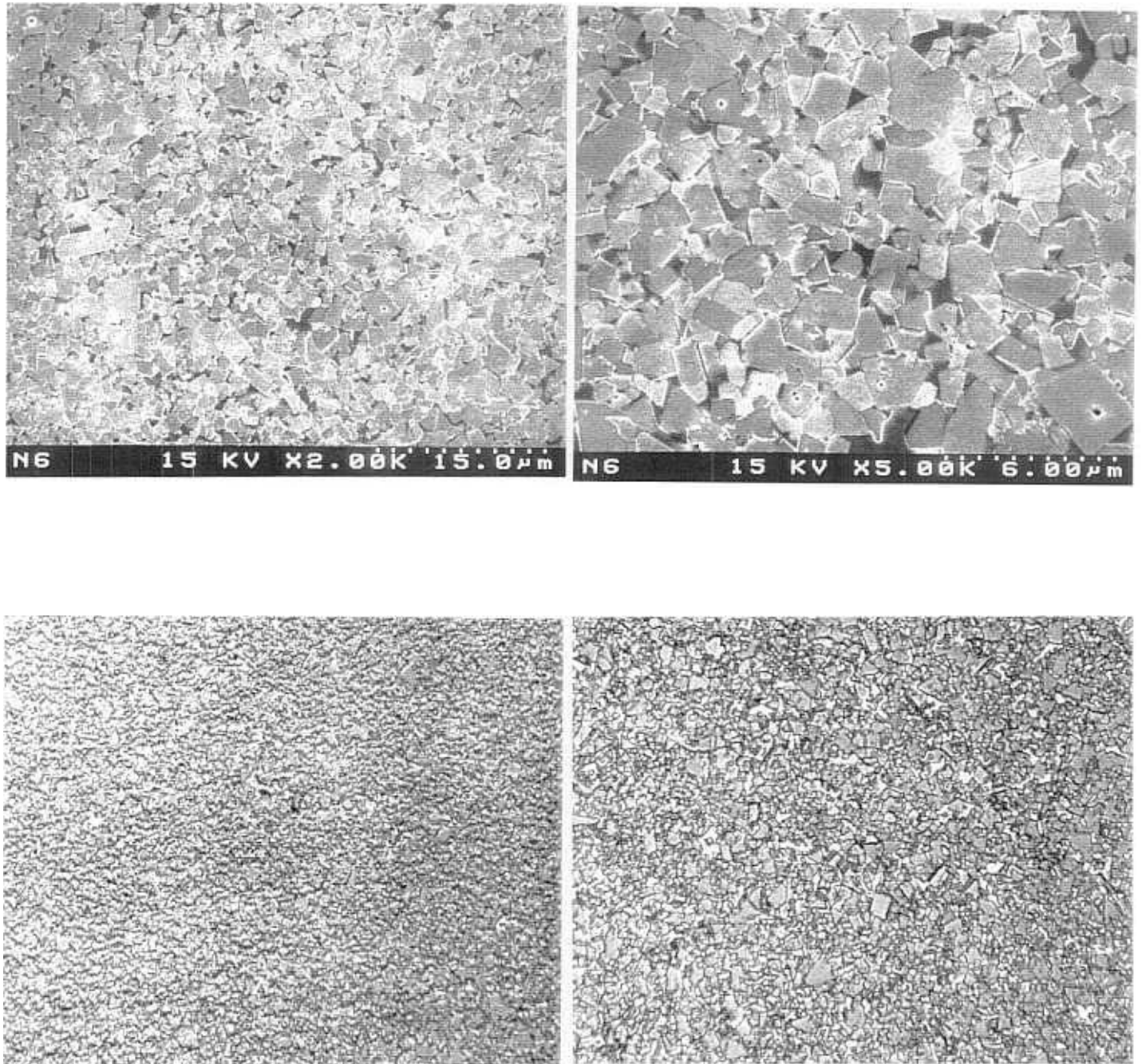


Fig 22 SEM and optical micrographs of N6

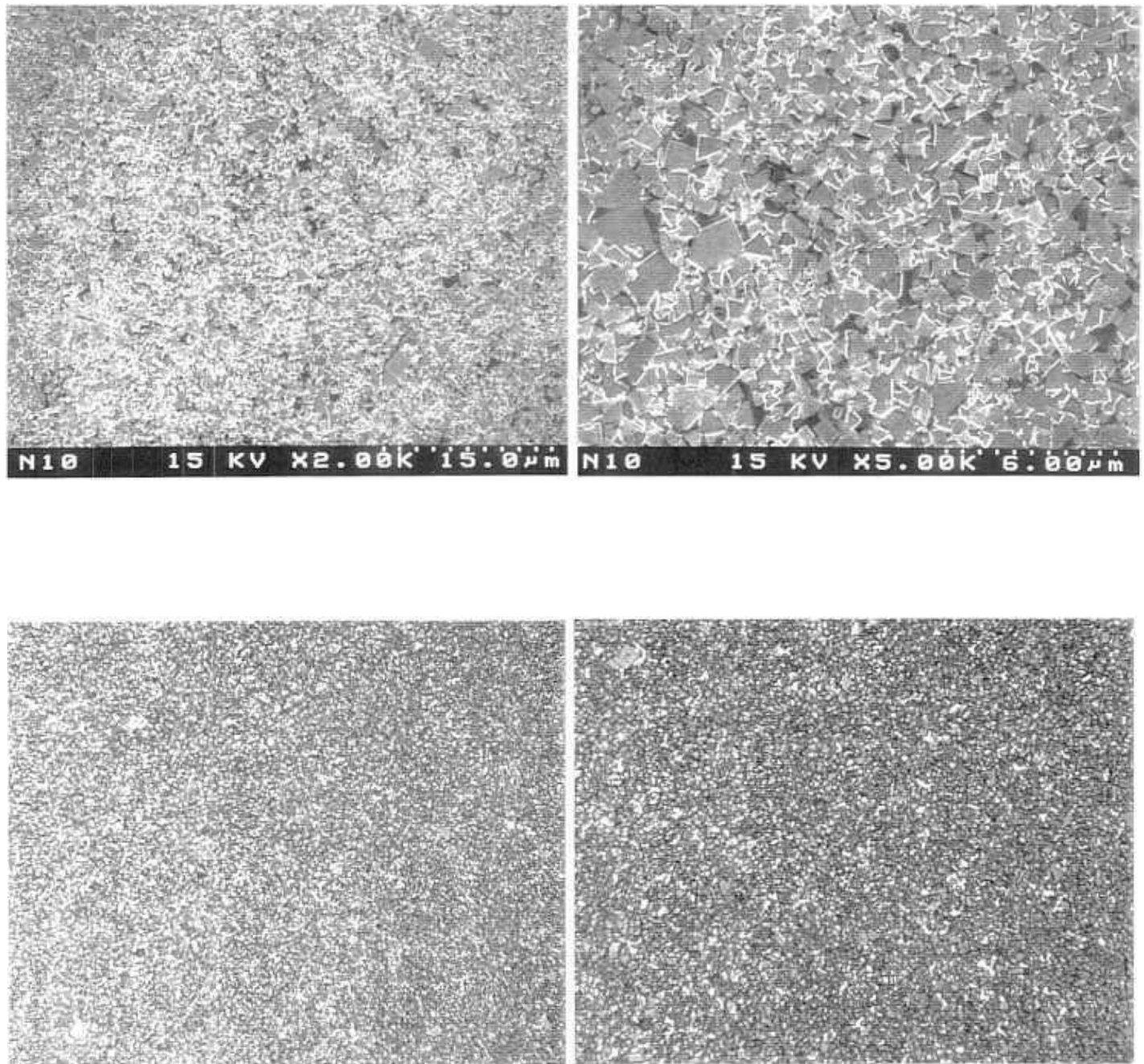


Fig 23 SEM and optical micrographs of N10

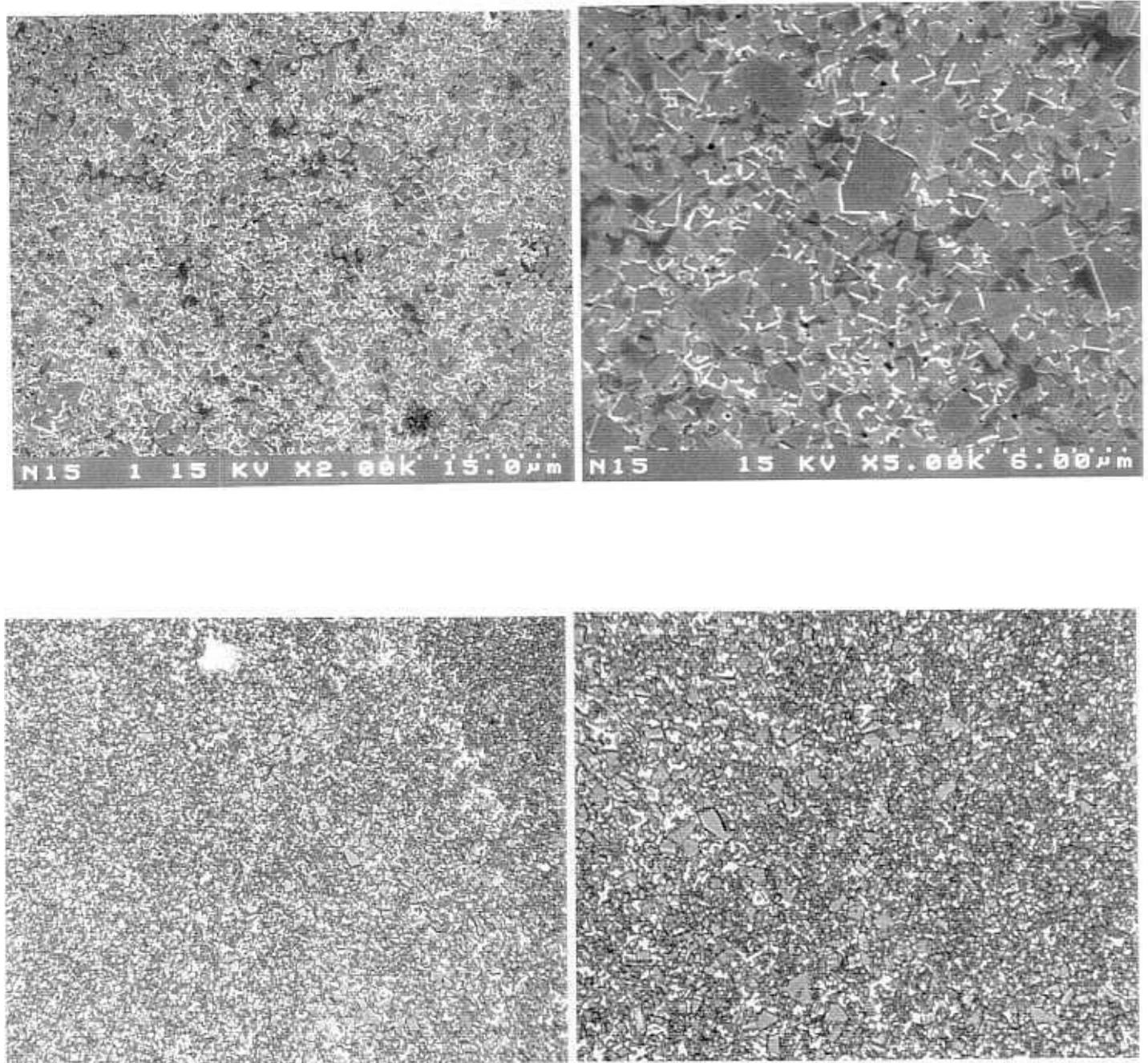


Fig 24 SEM and optical micrographs of N15

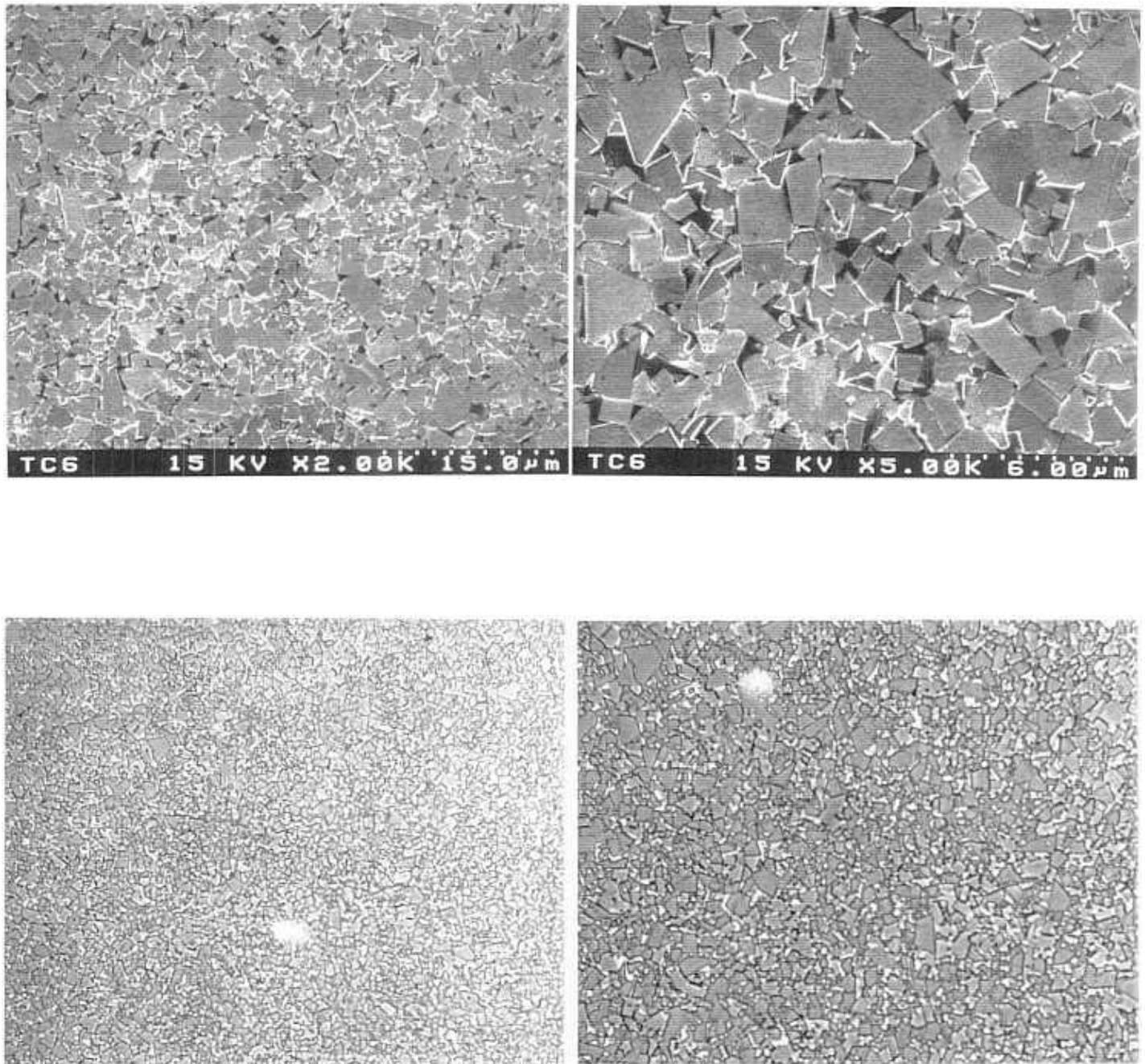


Fig 25 SEM and optical micrographs of TC6

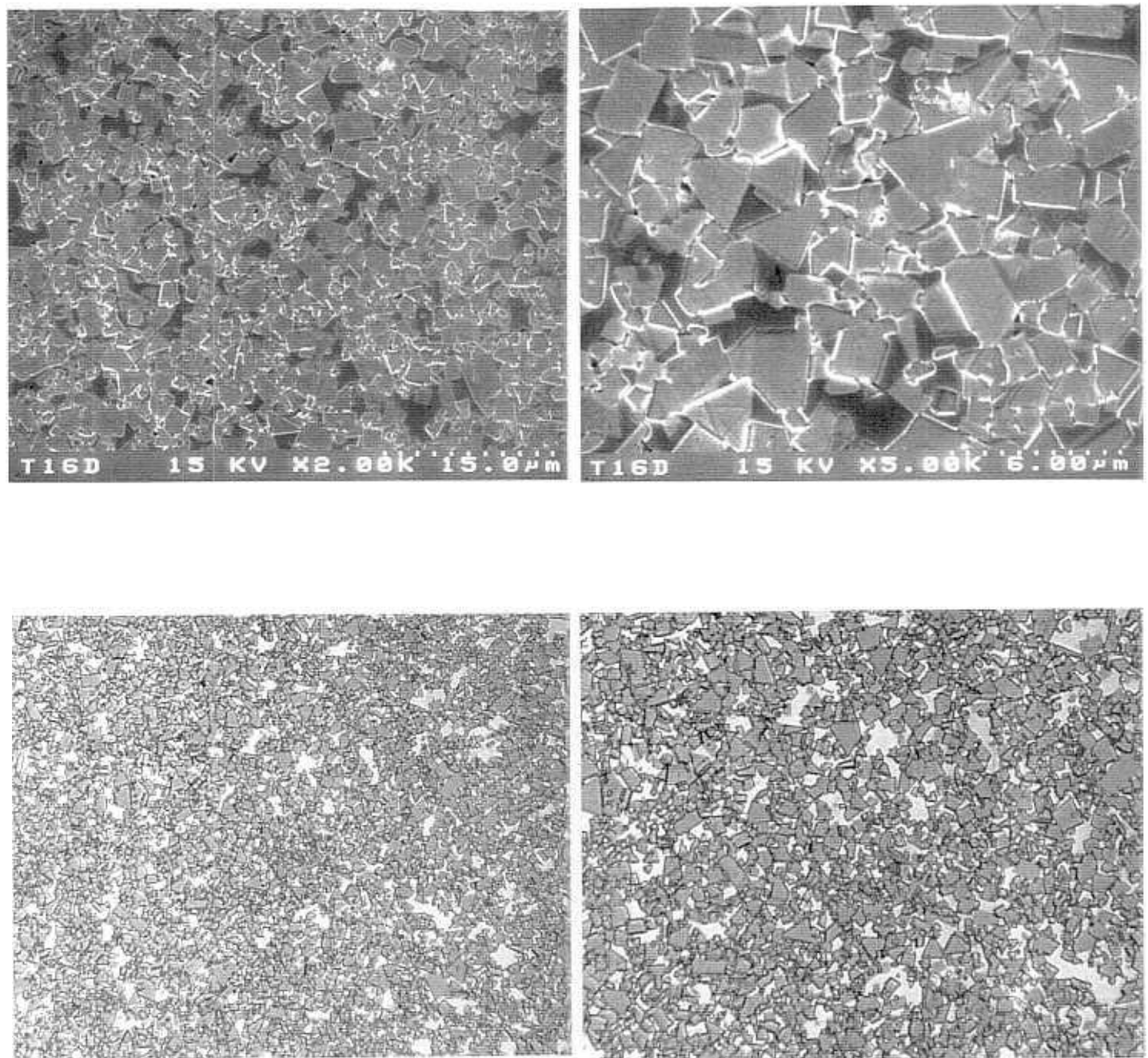


Fig 26 SEM and optical micrographs of T16D

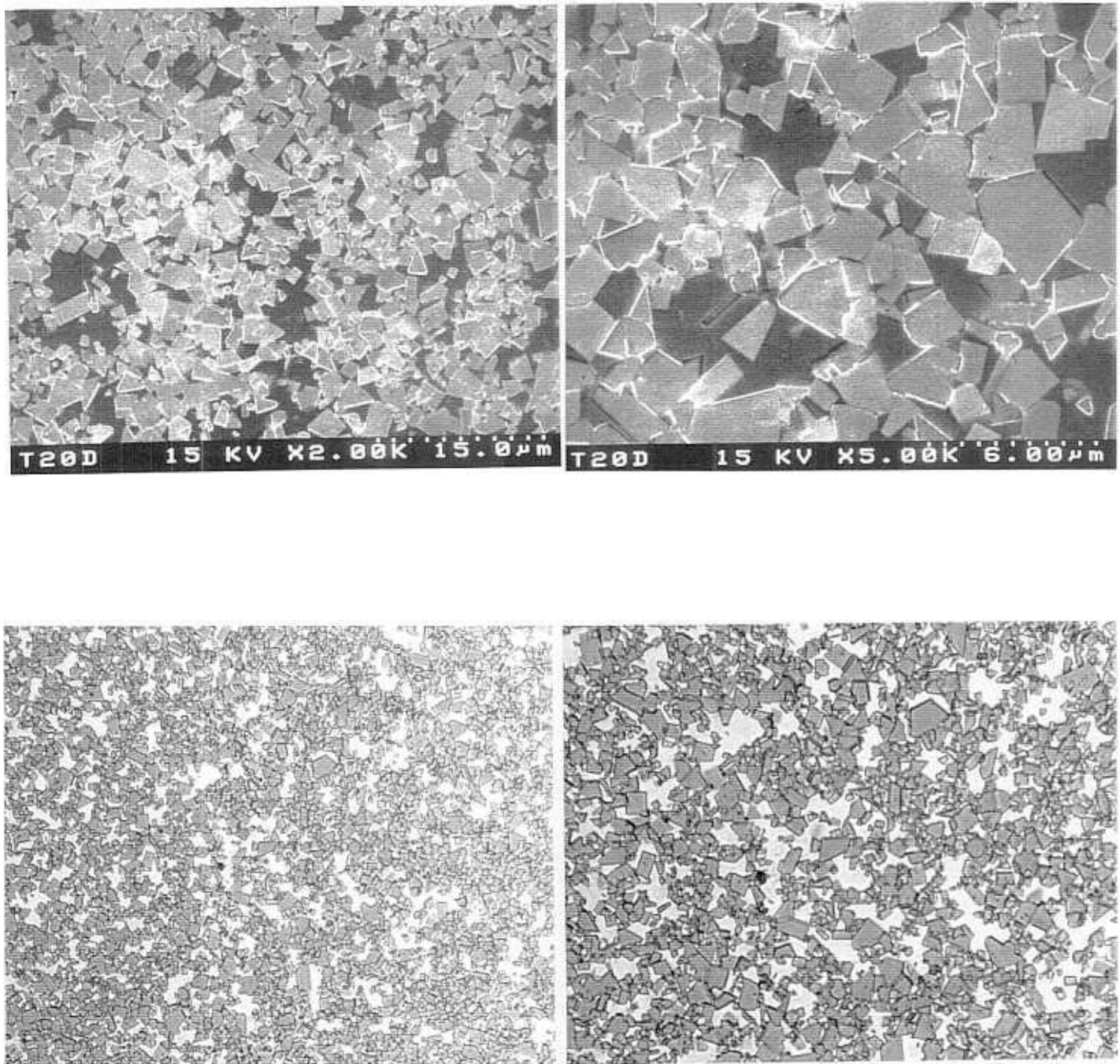


Fig 27 SEM and optical micrographs of T20D

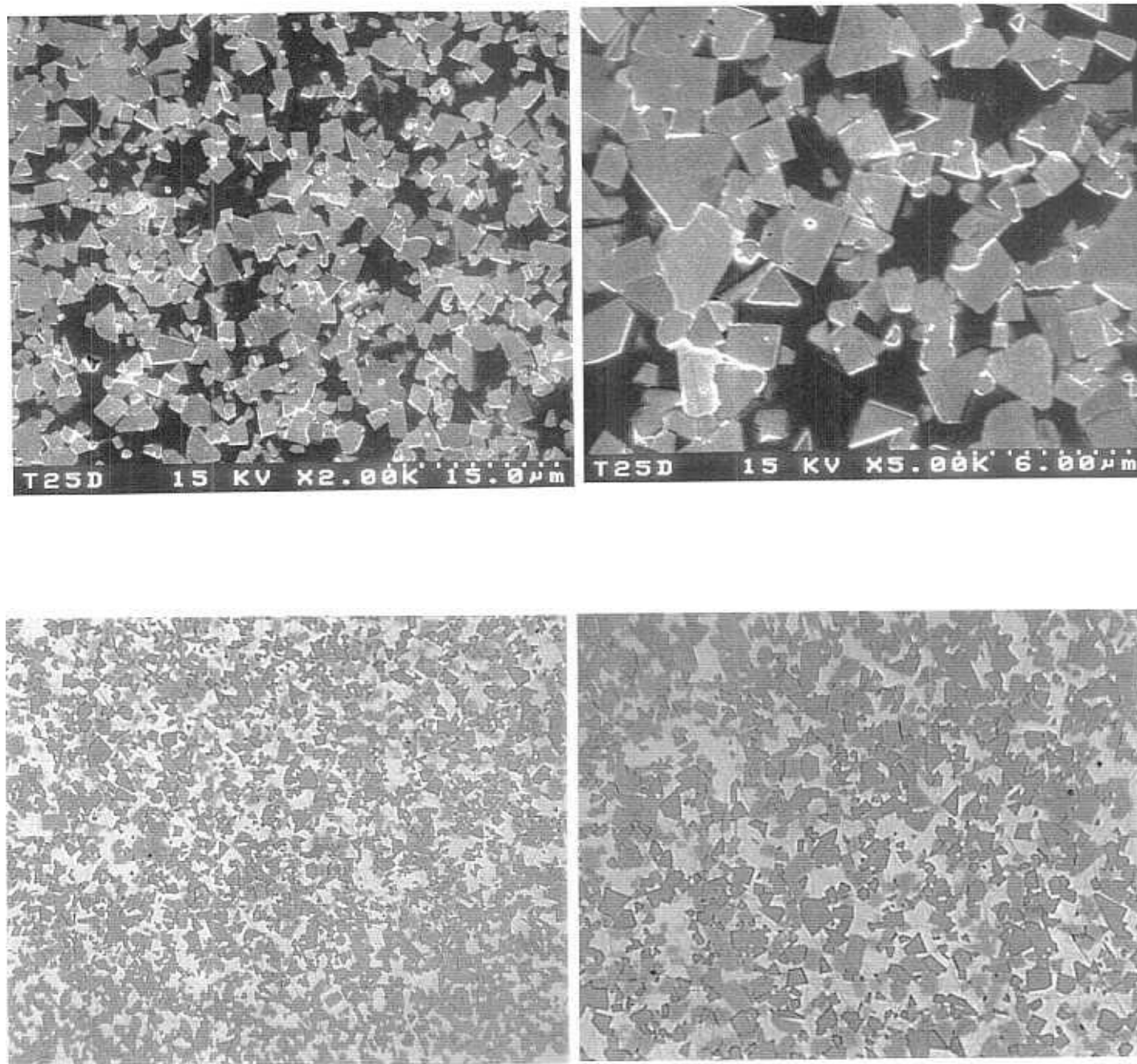


Fig 28 SEM and optical micrographs of T25D

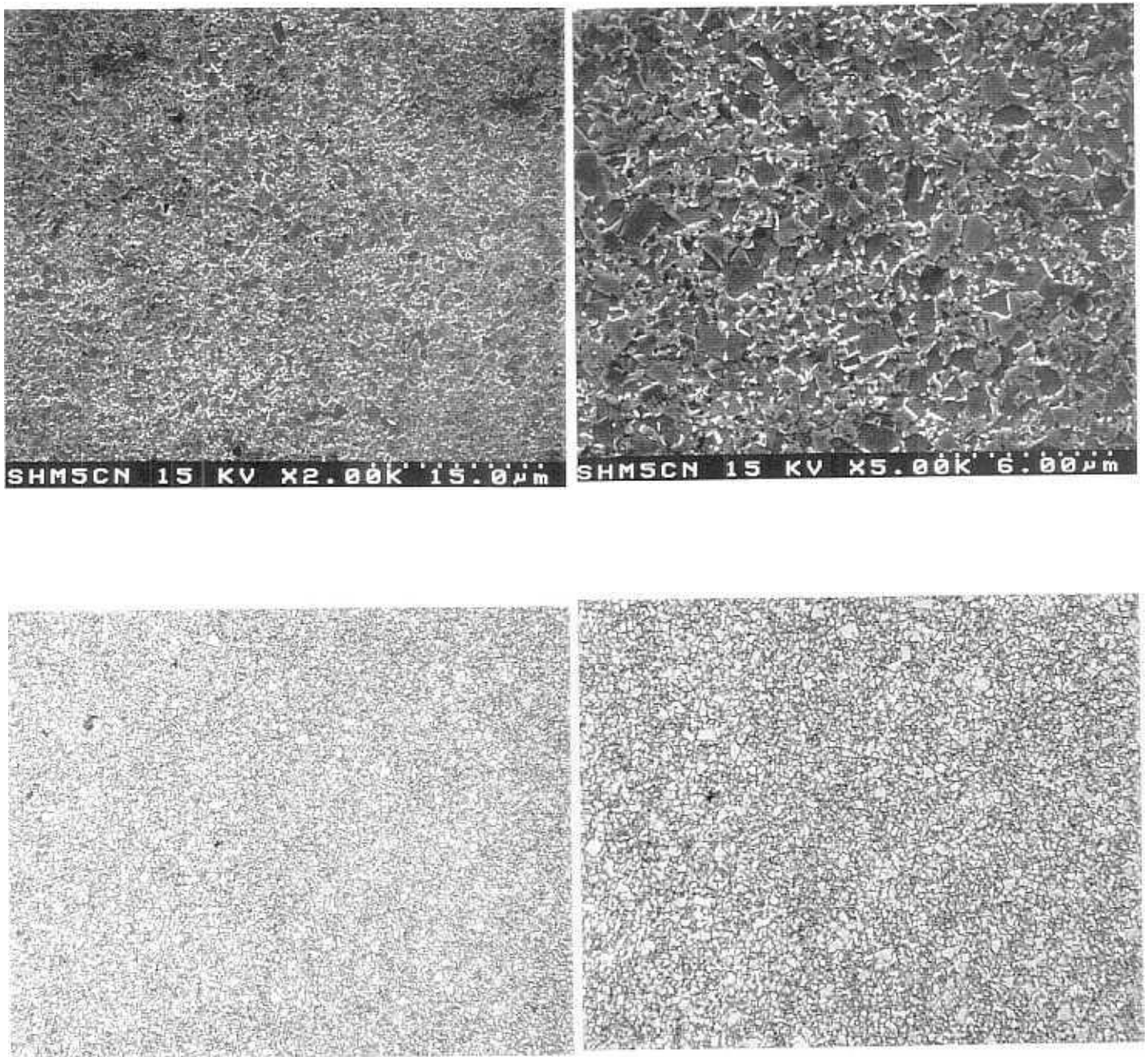


Fig 29 SEM and optical micrographs of SHM5CN

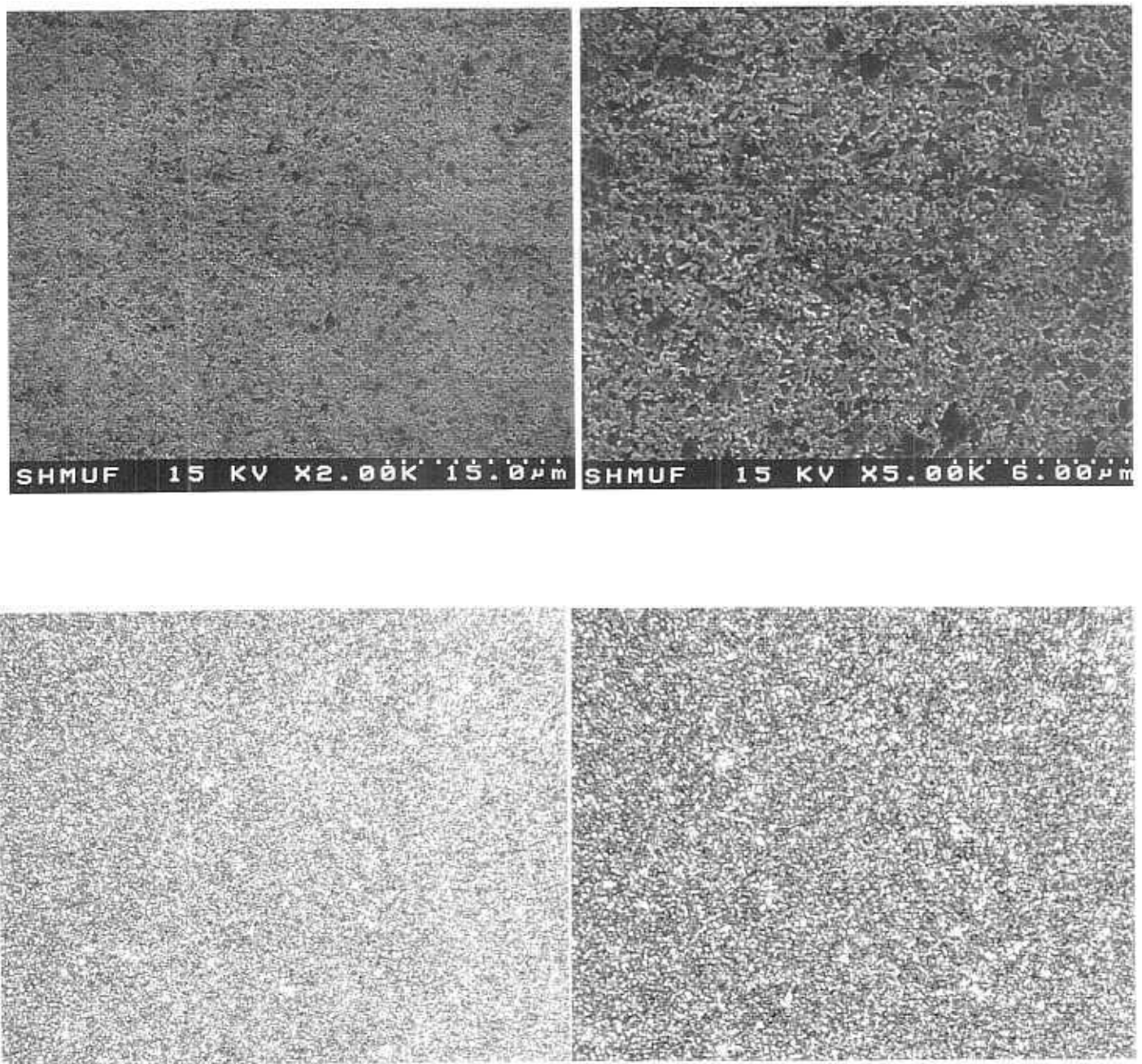


Fig 30 SEM and optical micrographs of SHMUF

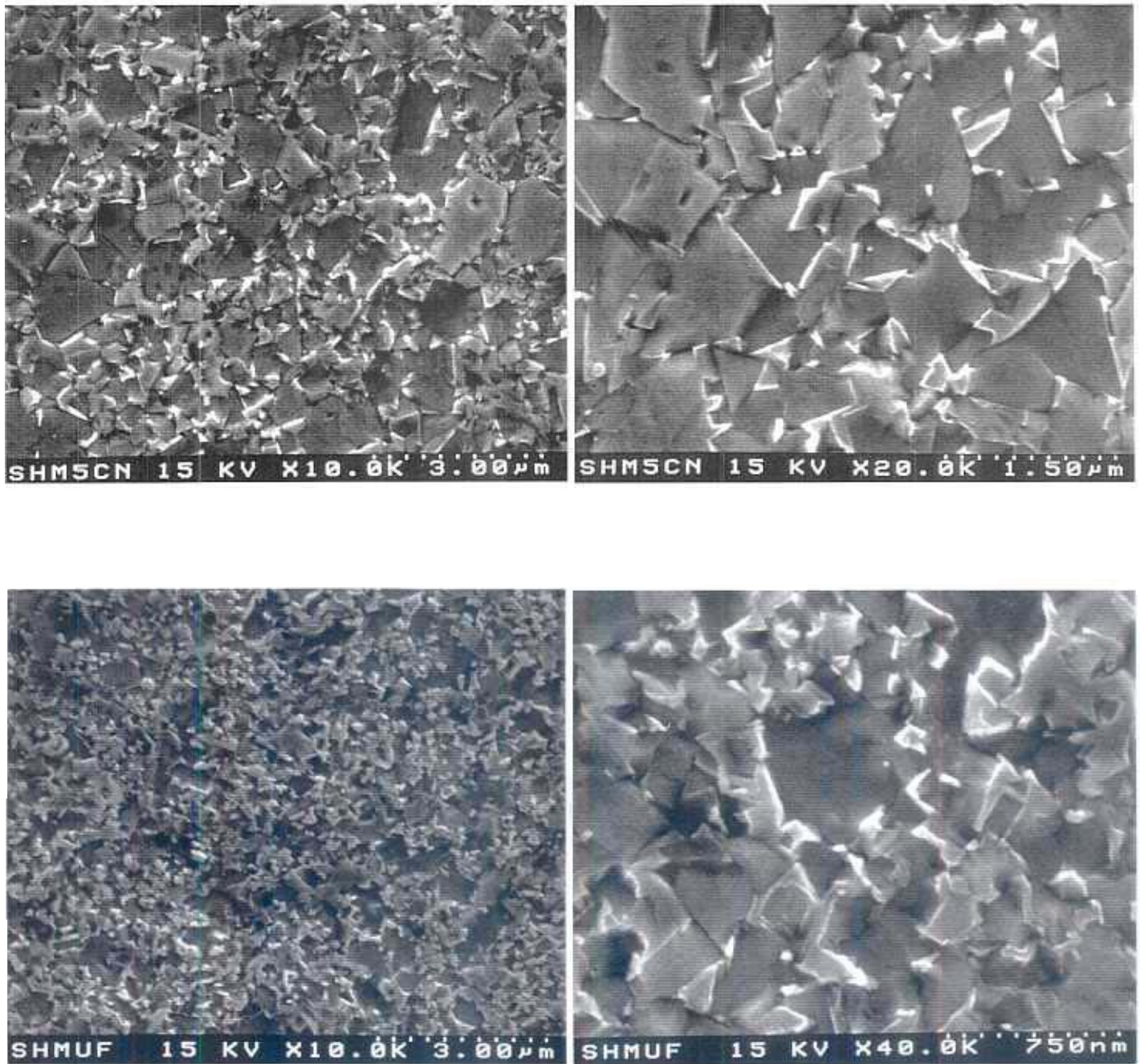


Fig 31 High magnification SEM micrographs of SHM5CN and SHMUF

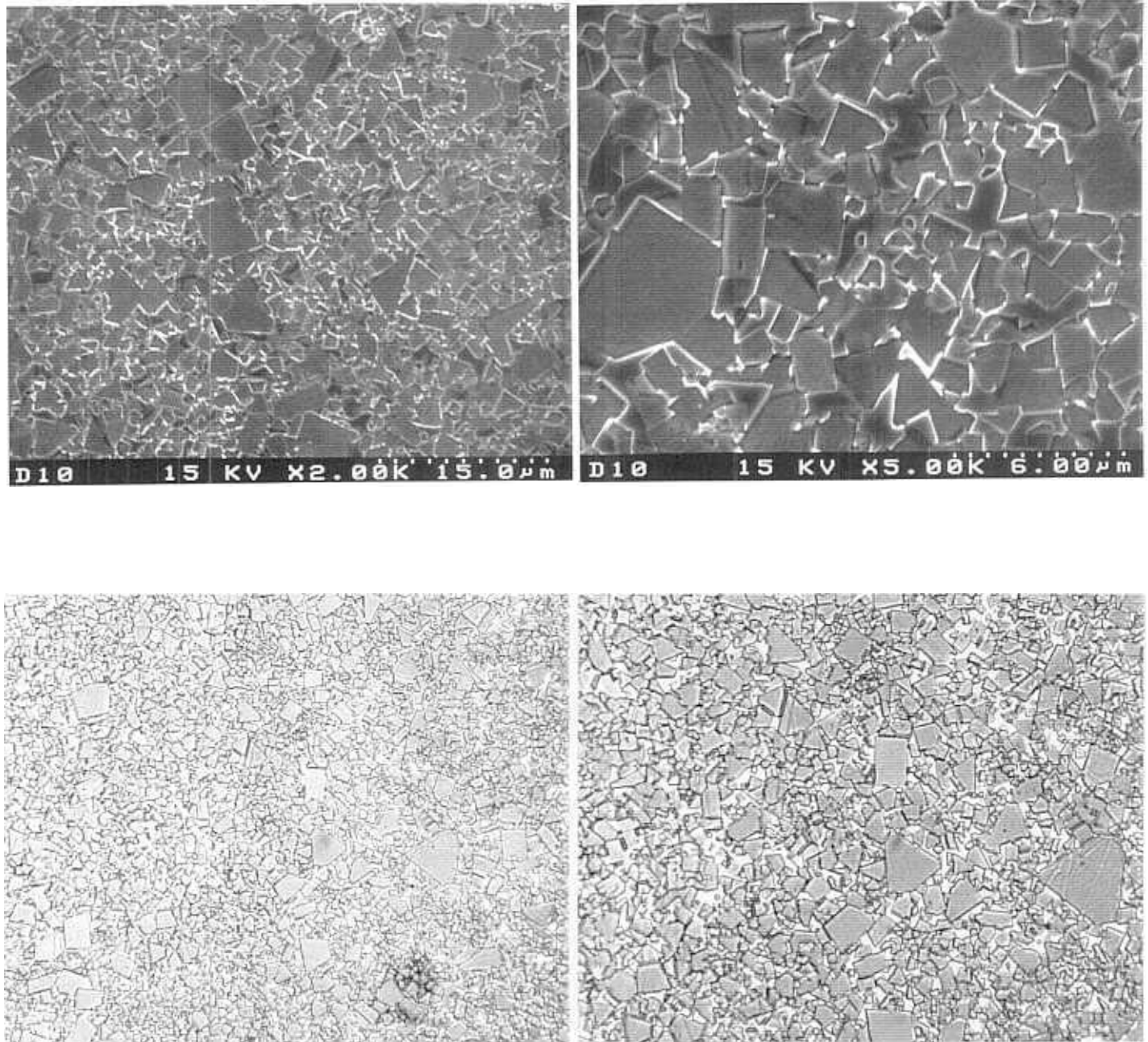


Fig 32 SEM and optical micrographs of D10

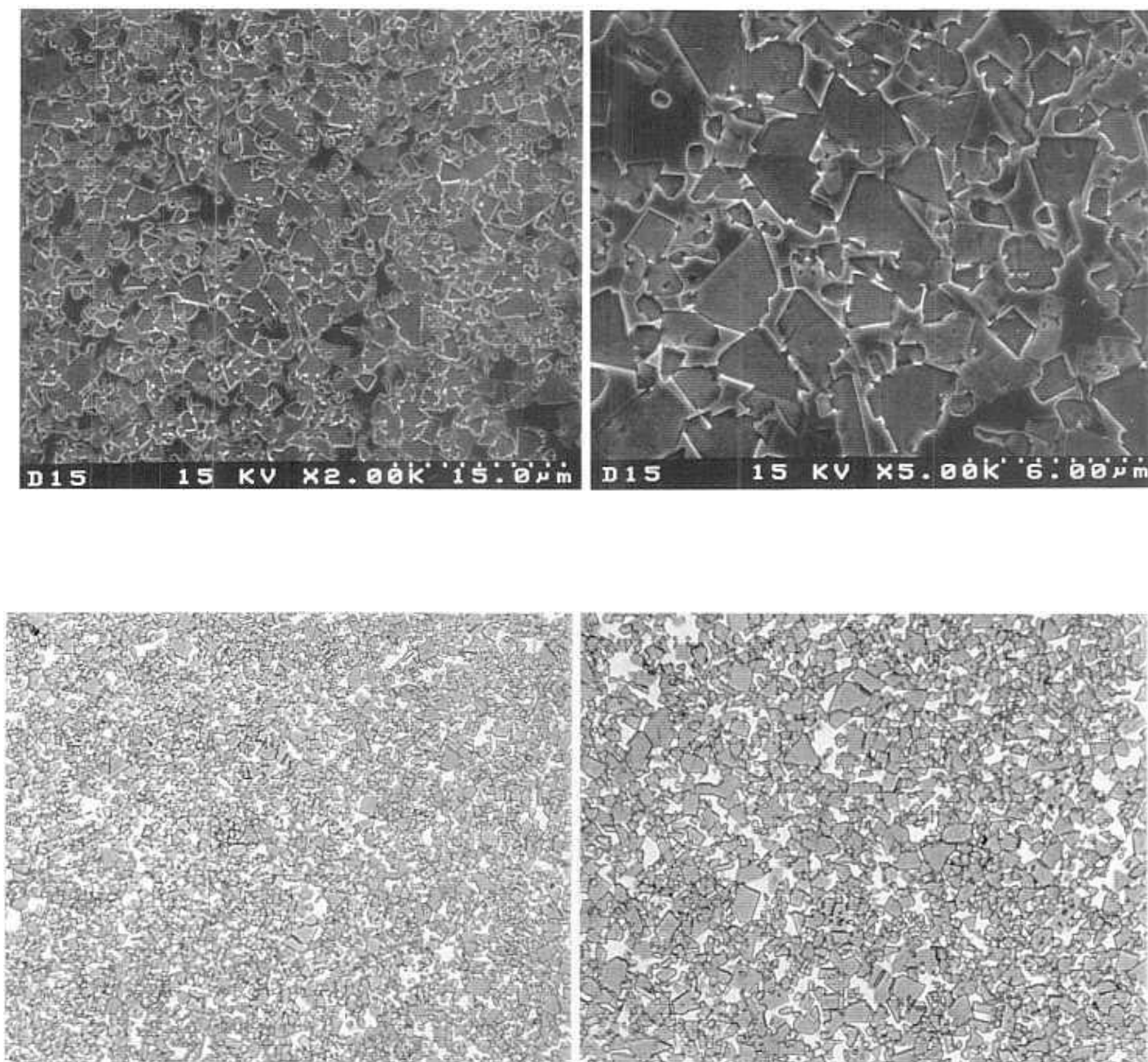


Fig 33 SEM and optical micrographs of D15

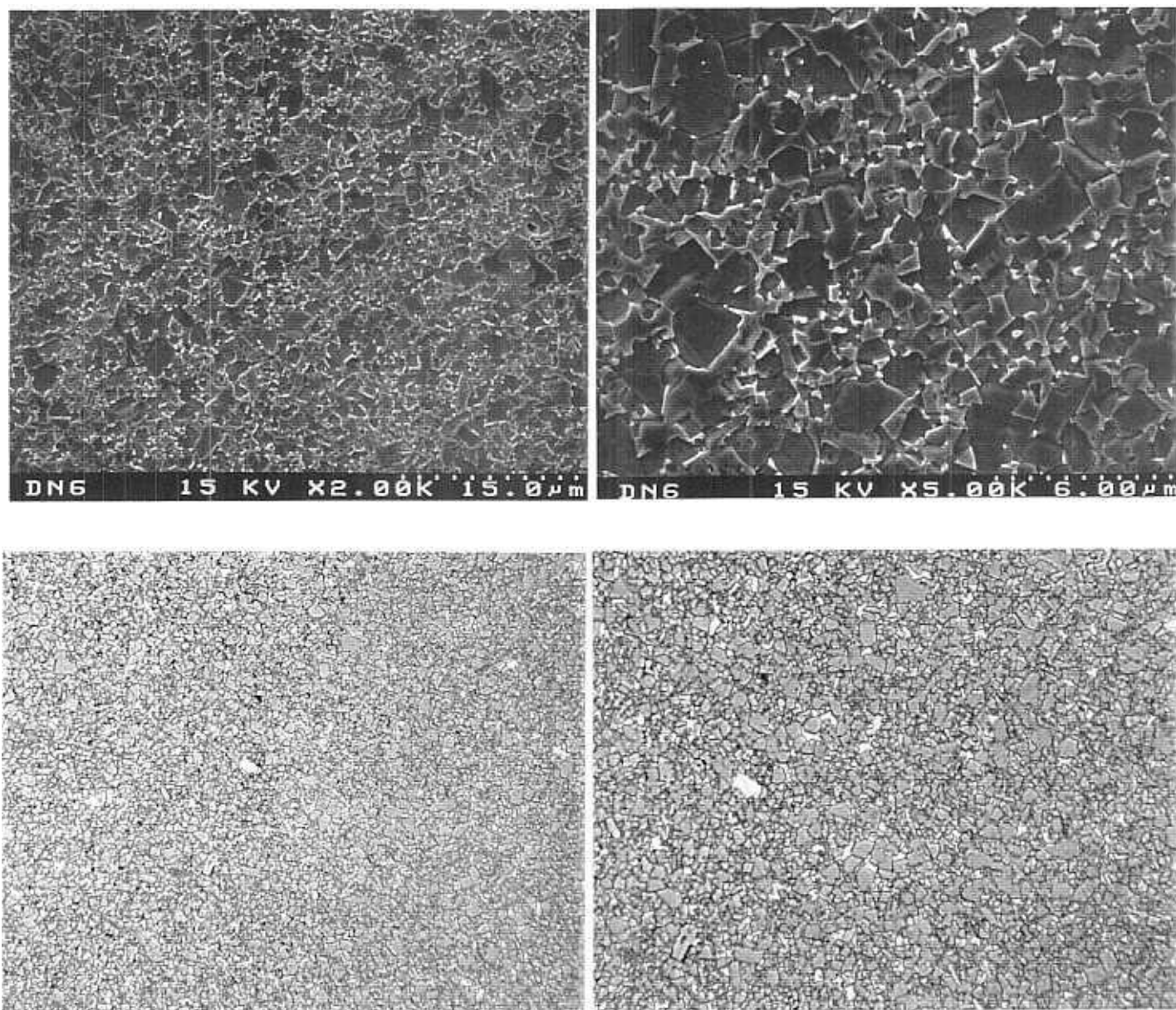


Fig 34 SEM and optical micrographs of DN6

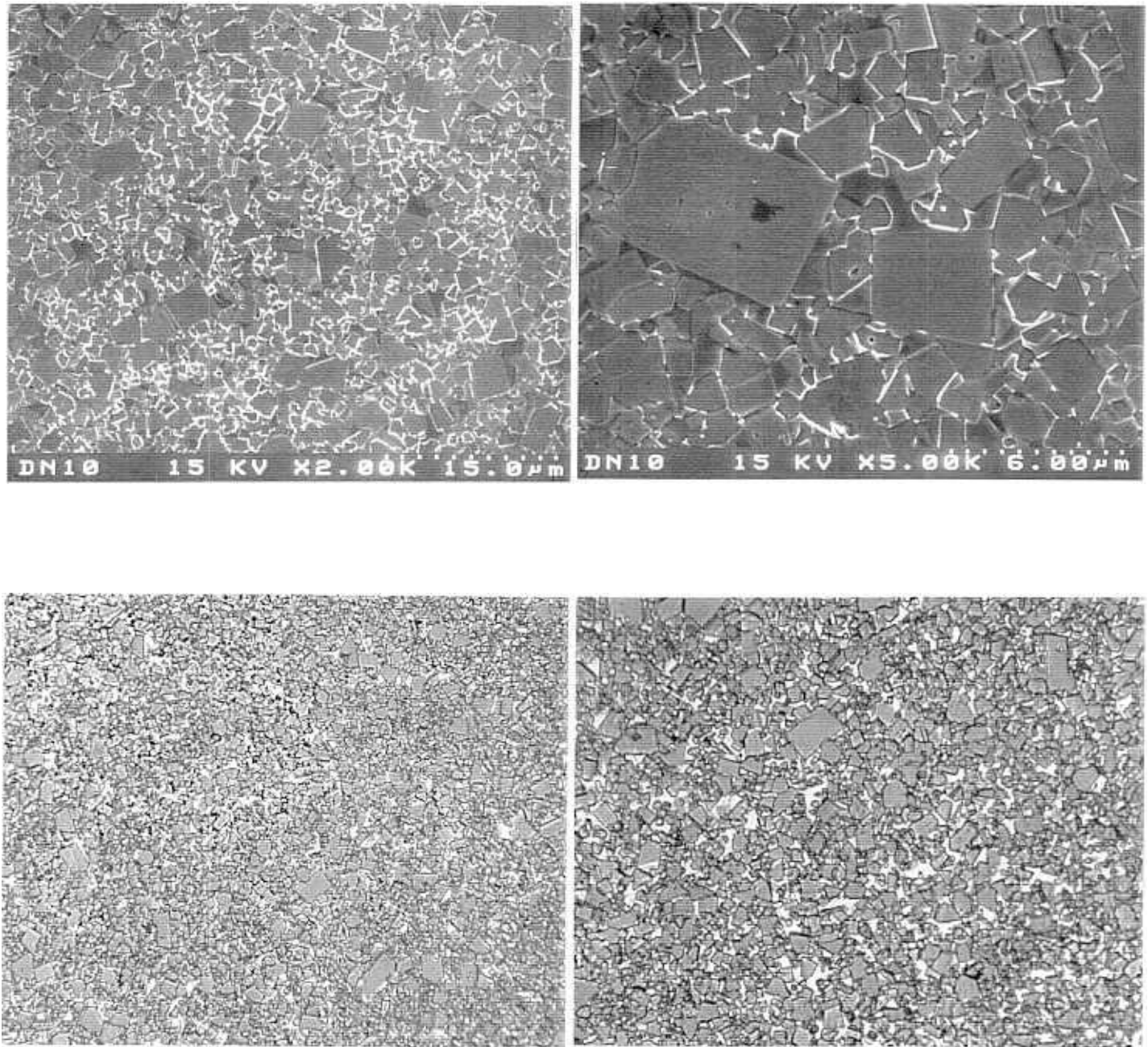


Fig 35 SEM and optical micrographs of DN10

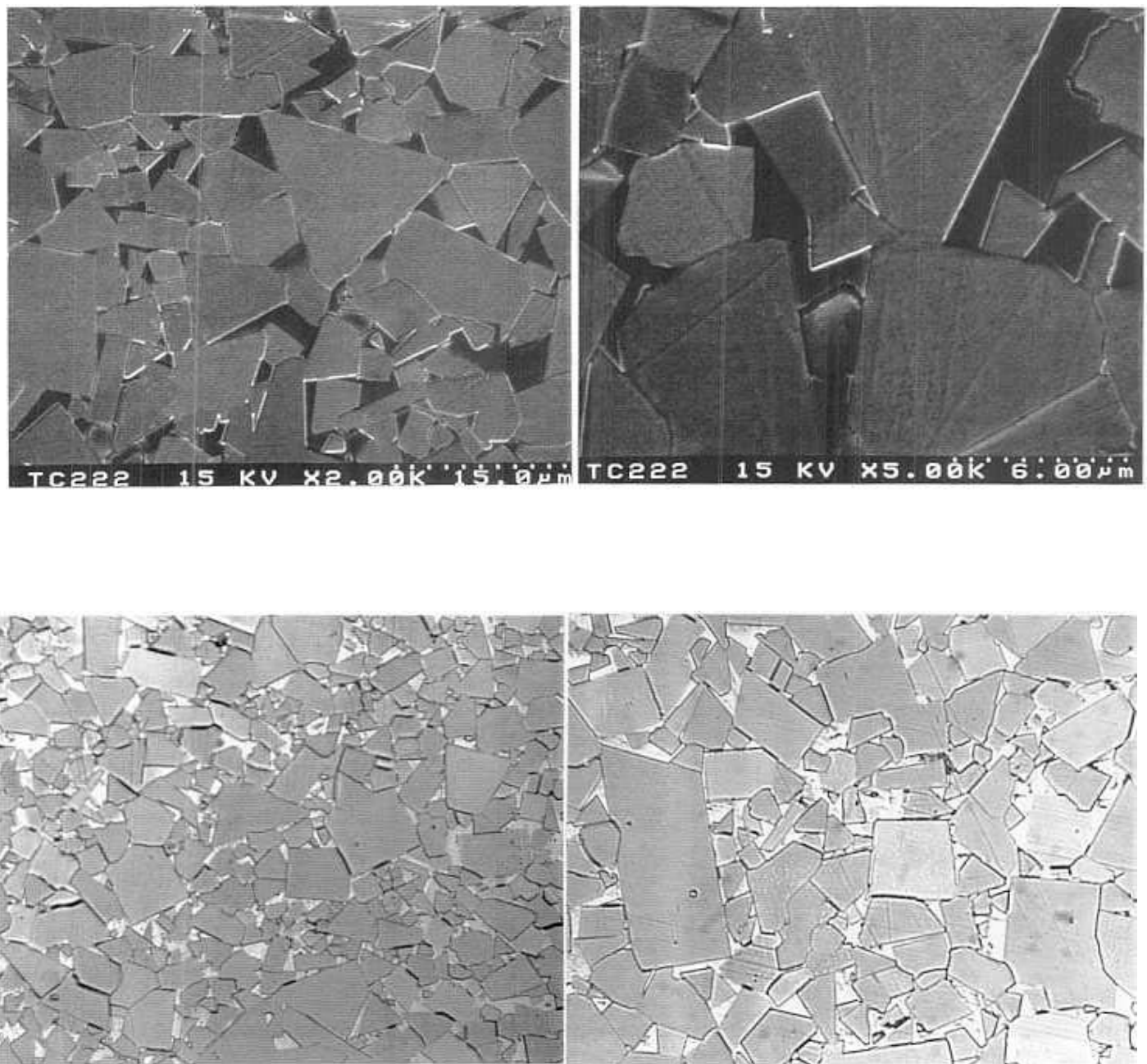


Fig 36 SEM and optical micrographs of TC222

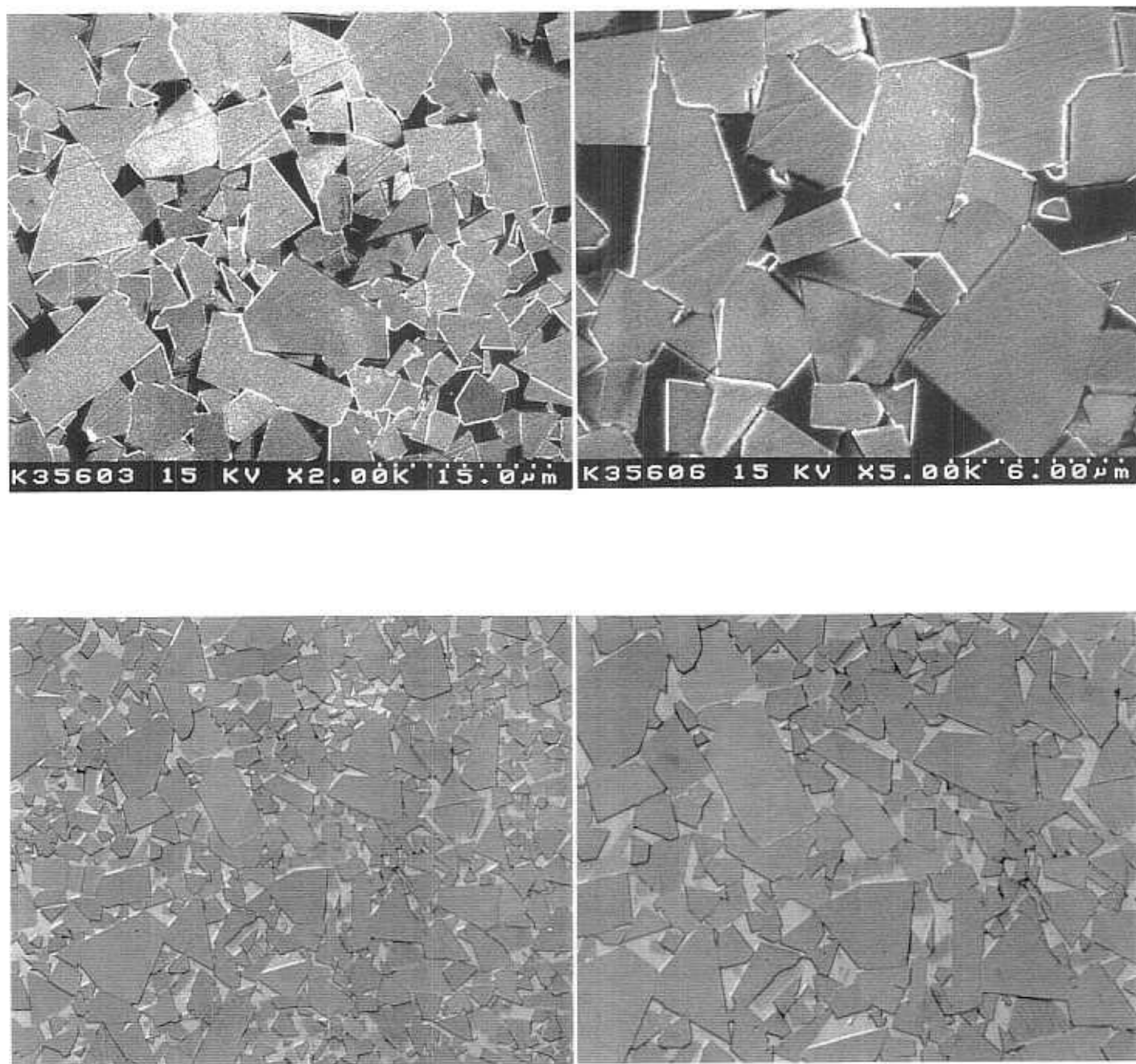


Fig 37 SEM and optical micrographs of K3560

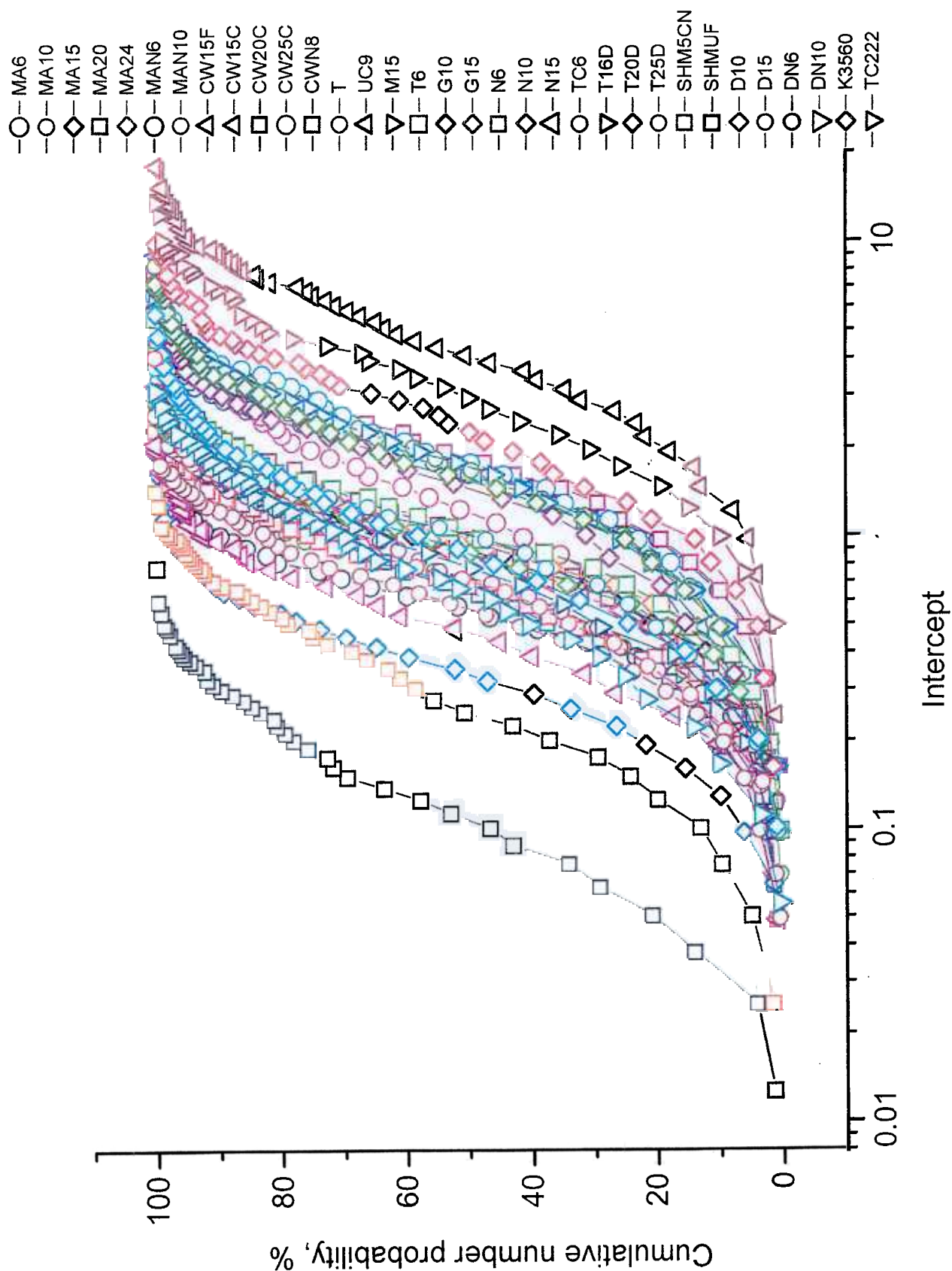


Fig 38 Cumulative number distribution of intercept data for all the materials

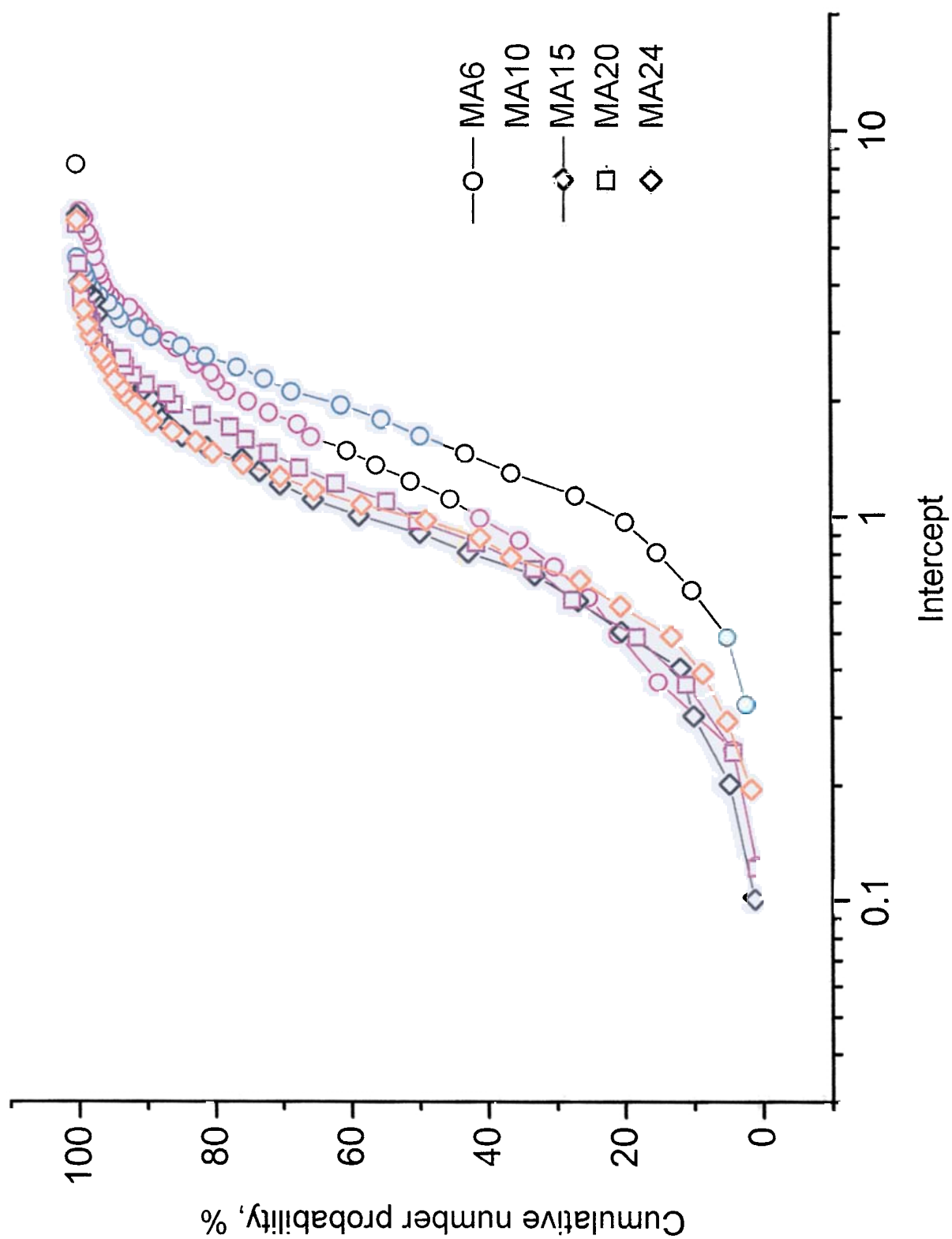


Fig 39 Cumulative number distributions for MA6, MA10, MA15, MA20 and MA24

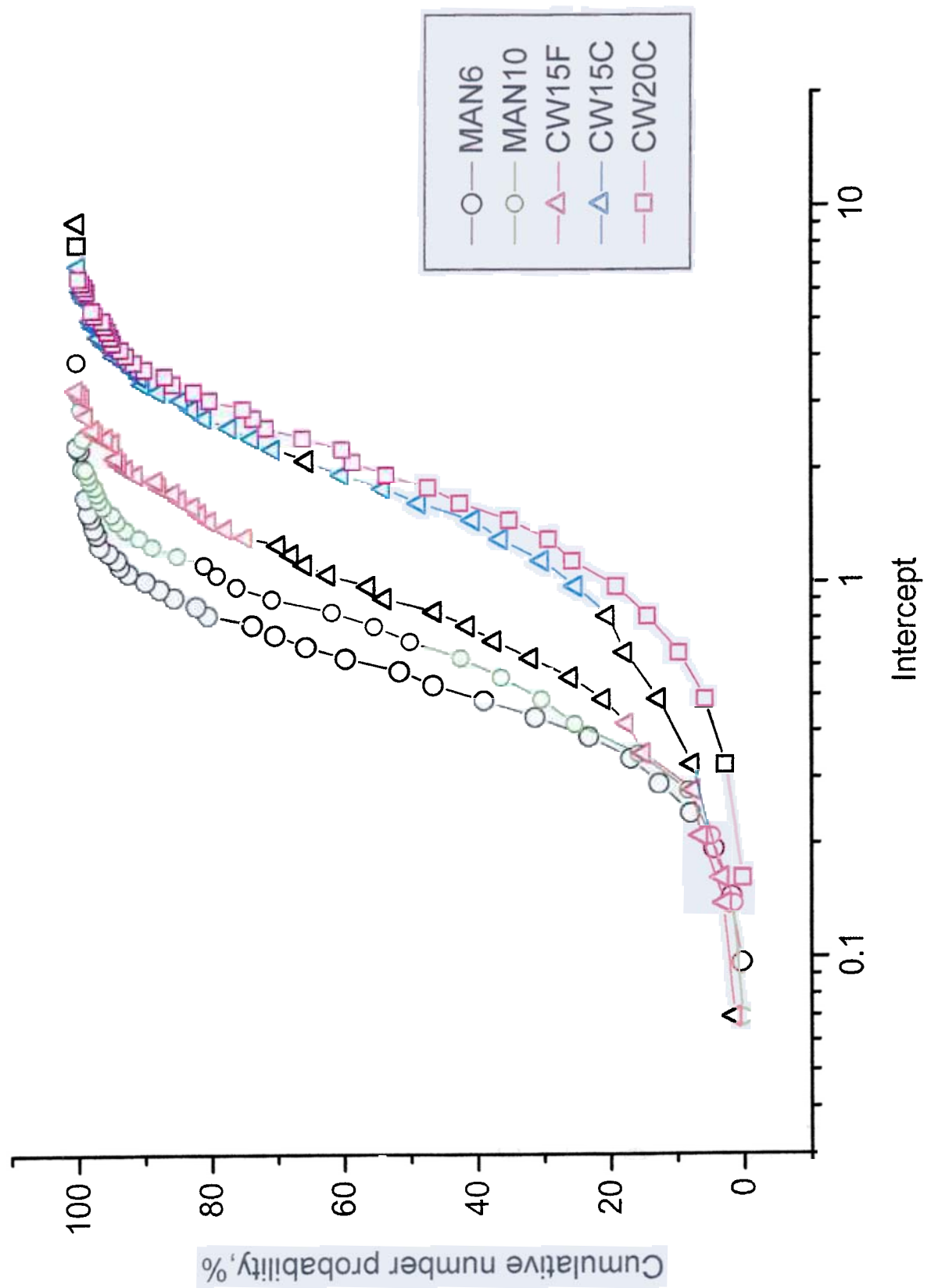


Fig 40 Cumulative number distributions for MAN6, MAN10, CW15F, CW15C and CW20C

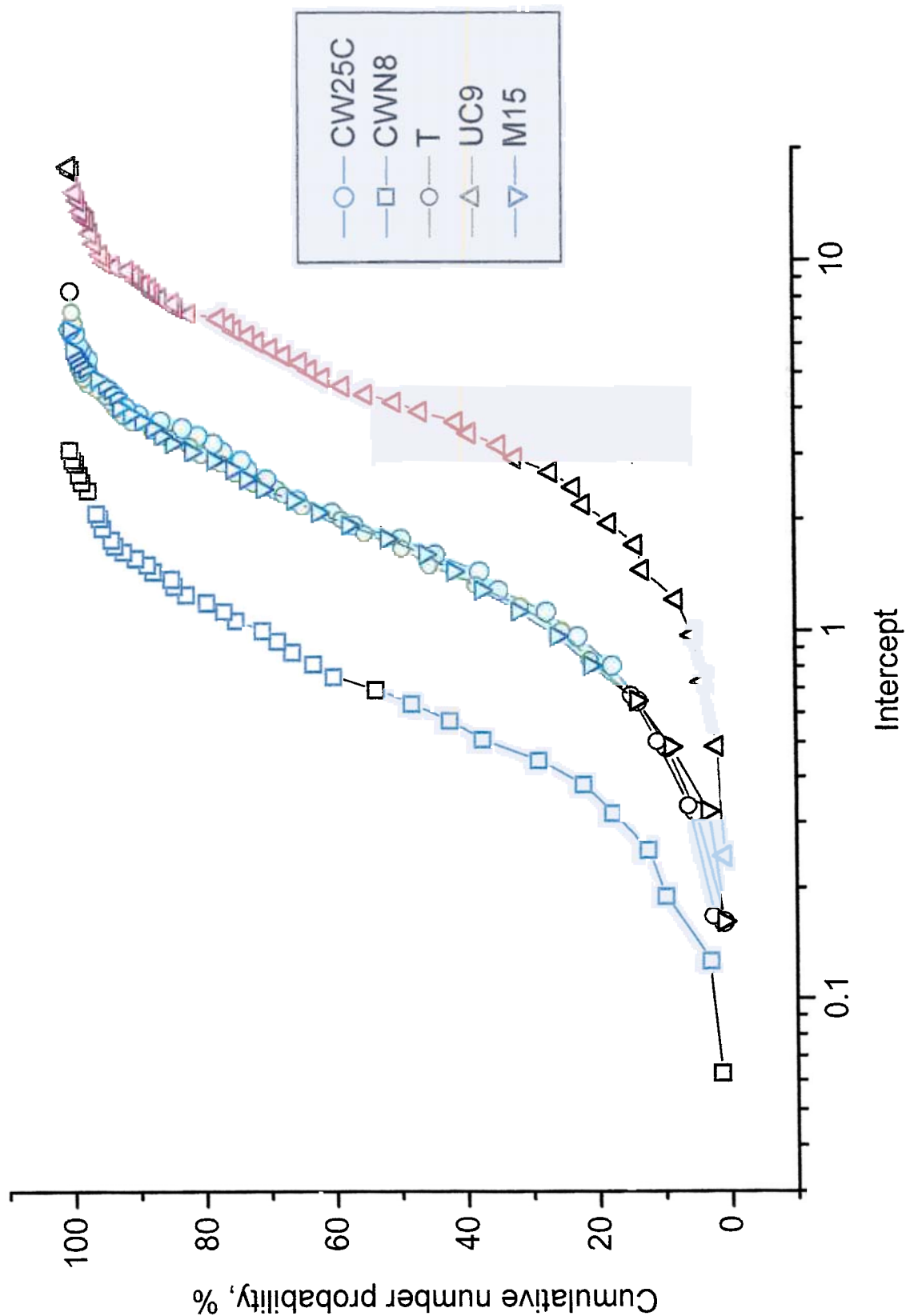


Fig 41 Cumulative number distributions for CW25C, CWN8, T, UC9 and M15

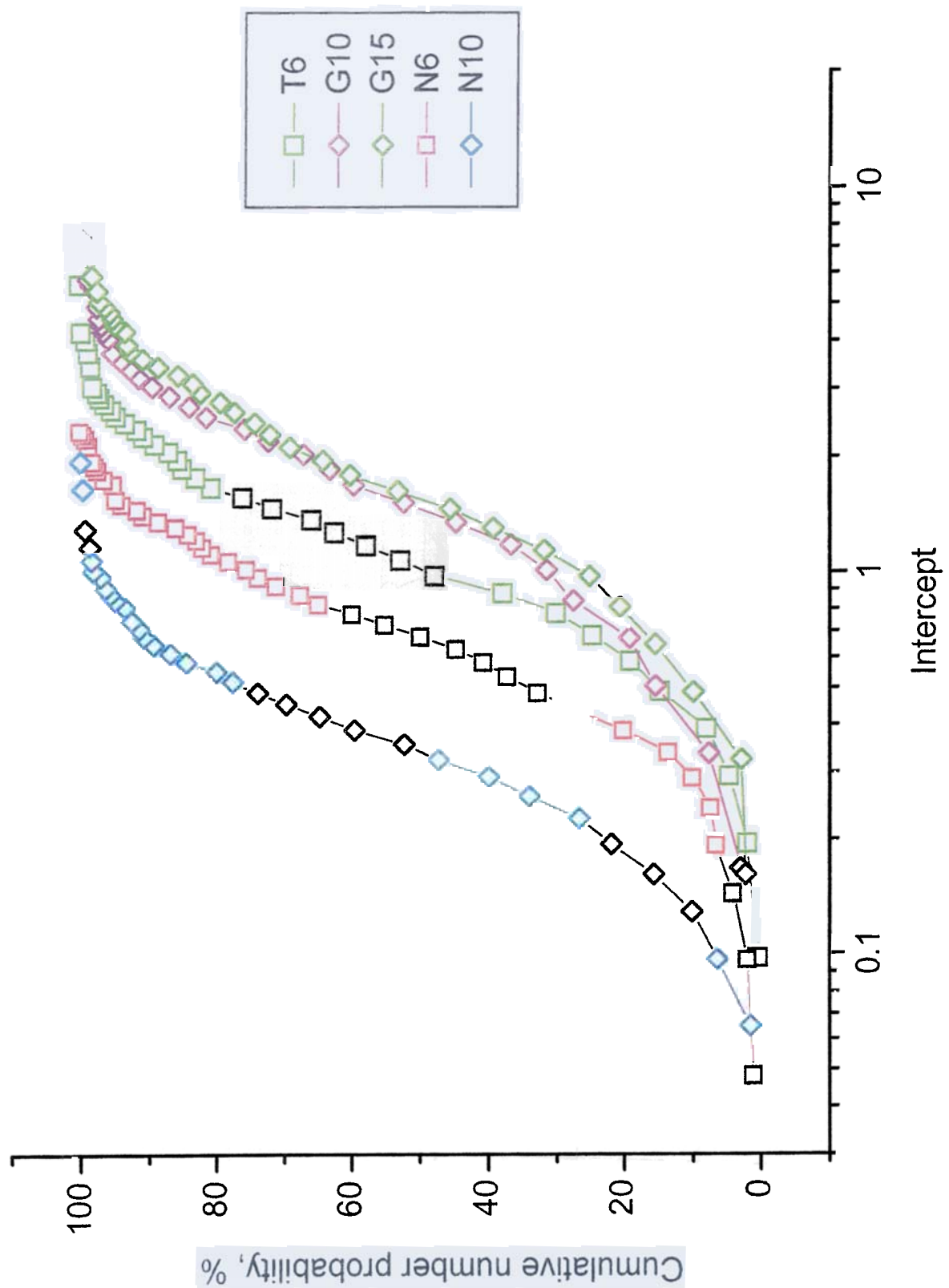


Fig 42 Cumulative number distributions for T6, G10, G15, N6 and N10

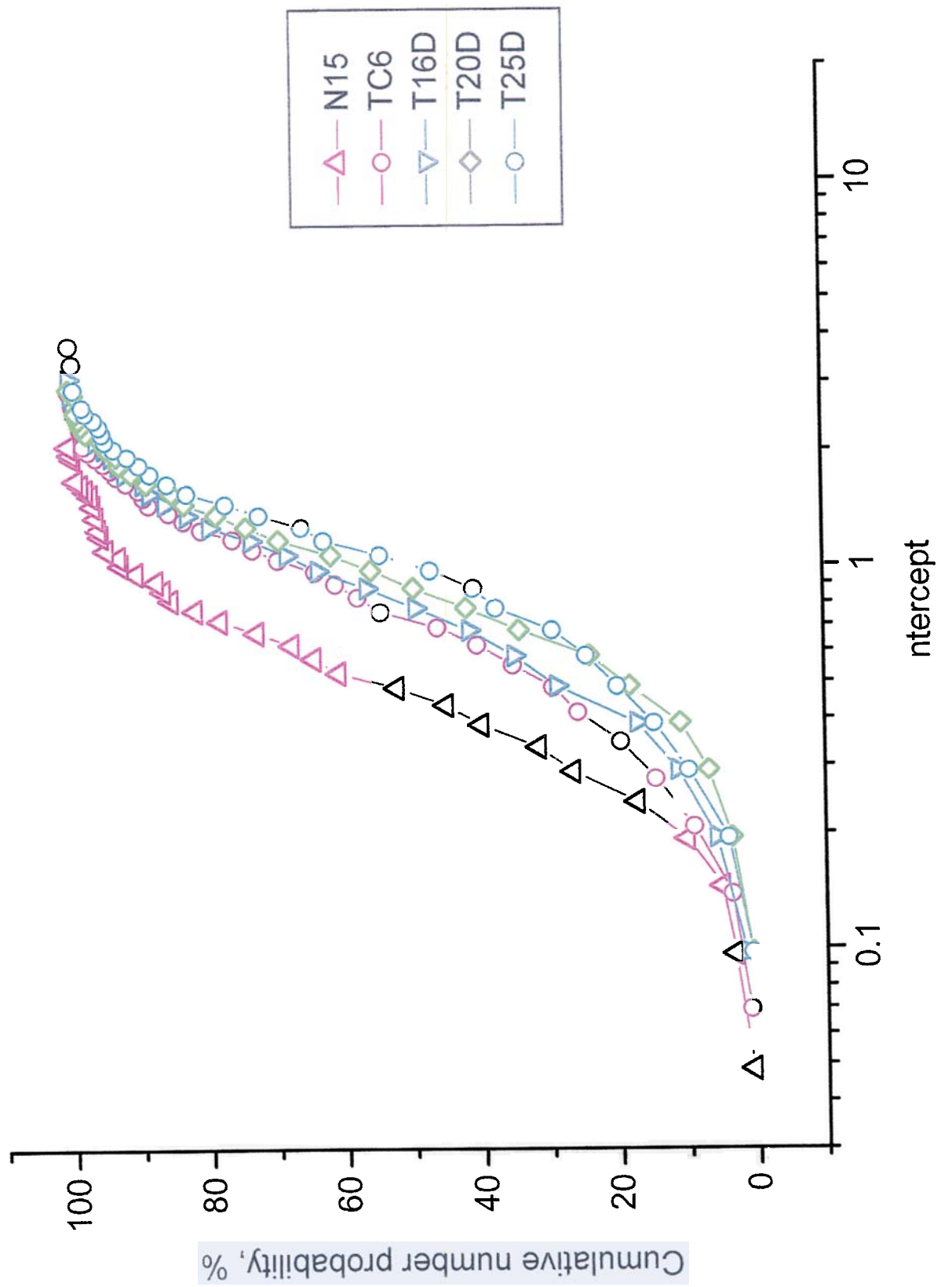


Fig 43 Cumulative number distributions for N15, TC6, T16D, T20D and T25D

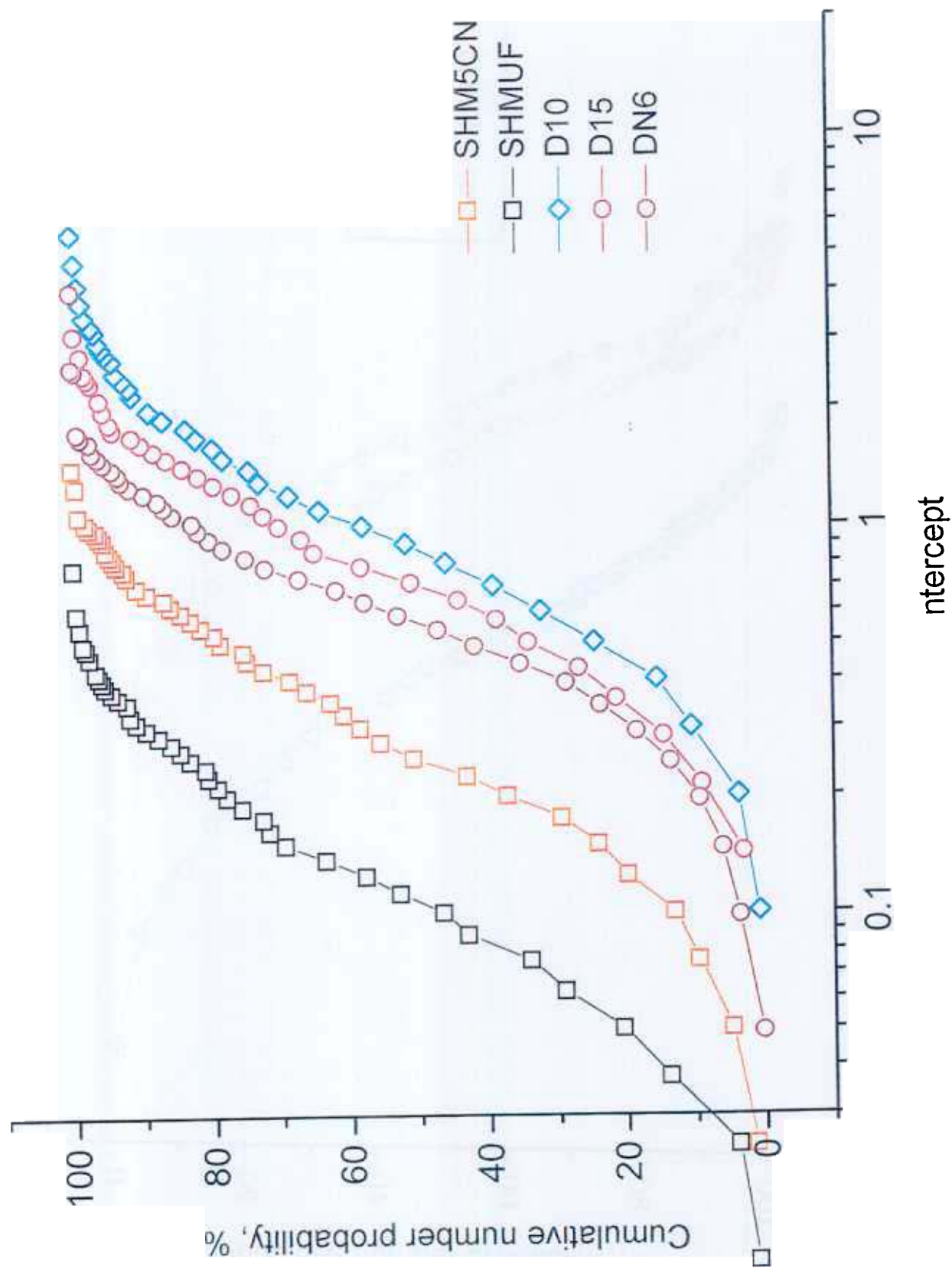


Fig 44 Cumulative number distributions for SHM5CN, SHMUF, D10, D15 and DN6

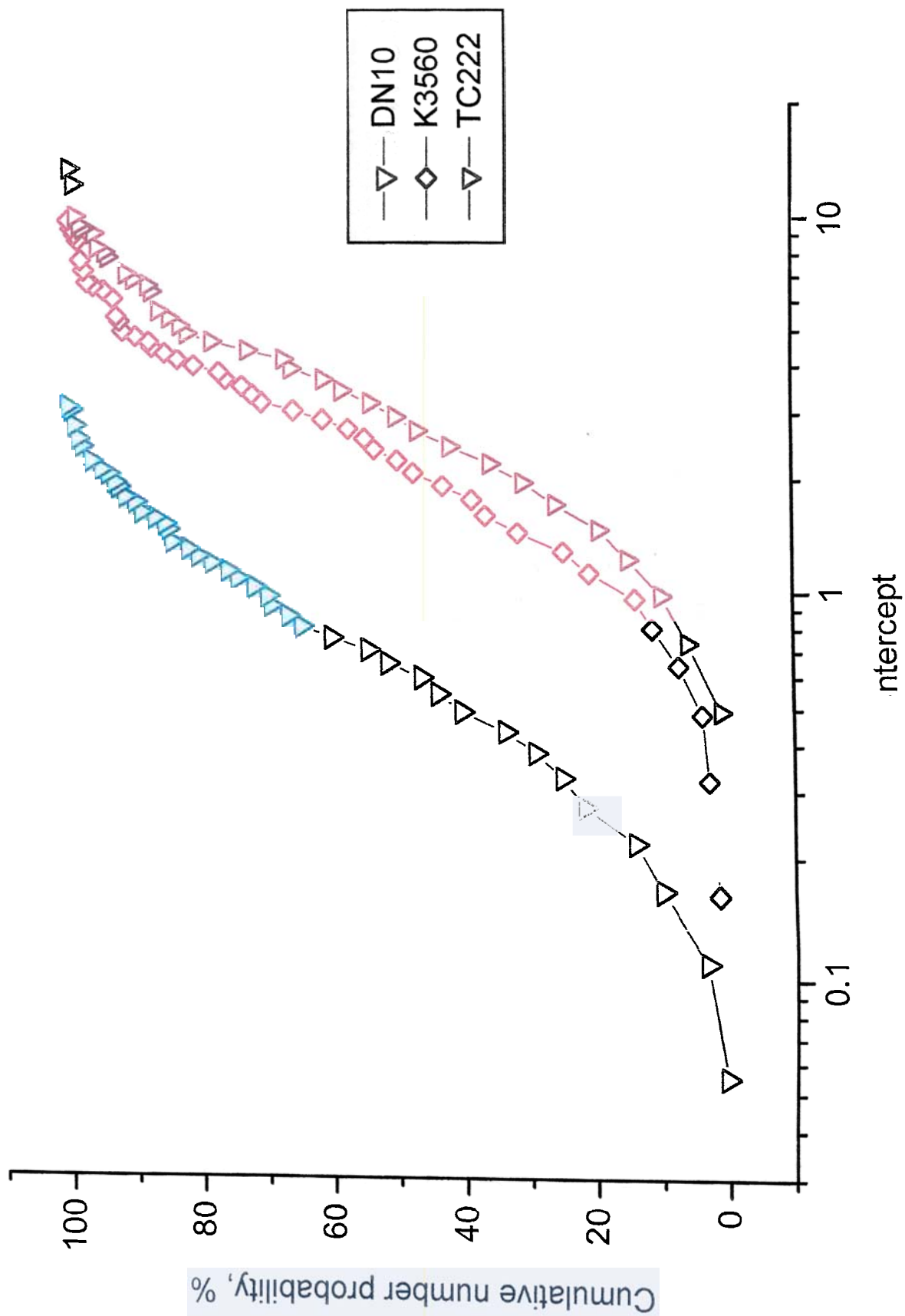


Fig 45 Cumulative number distributions for DN10, K3560 and TC222

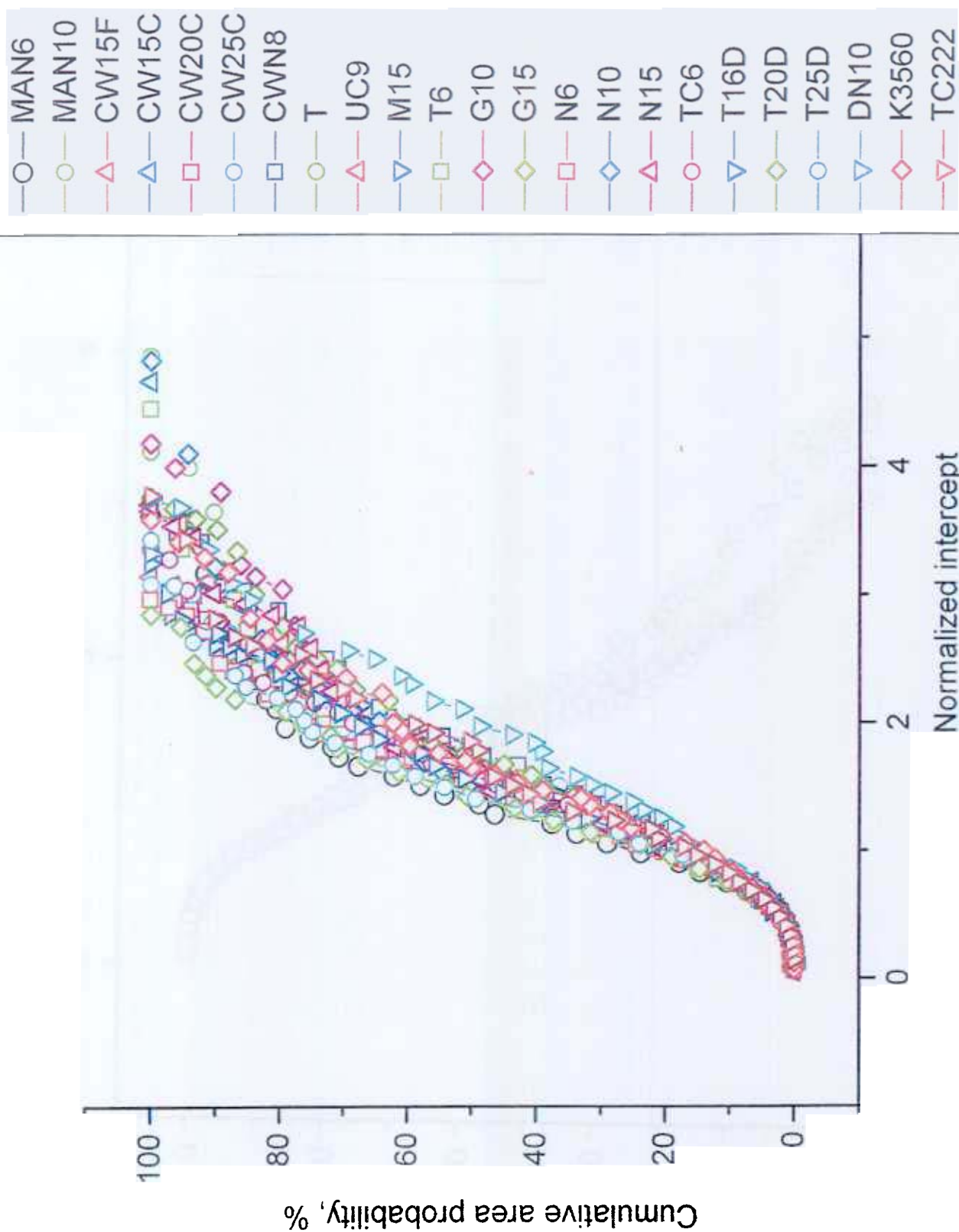


Fig 46 Size distribution of intercept squared data plotted against normalised intercepts for all the materials

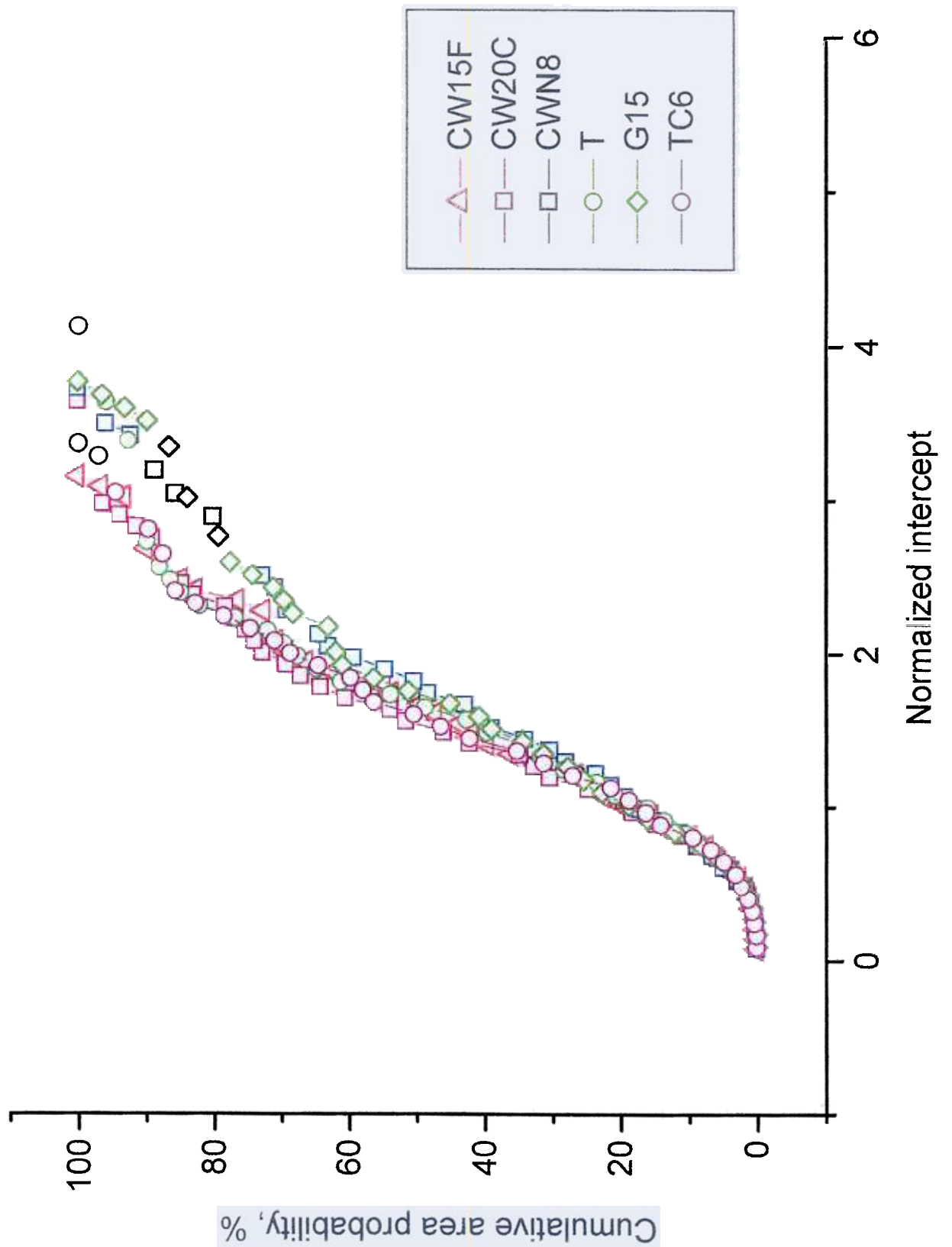


Fig 47 Cumulative size distributions for MA6, MA10, MA15, MA20 and MA24

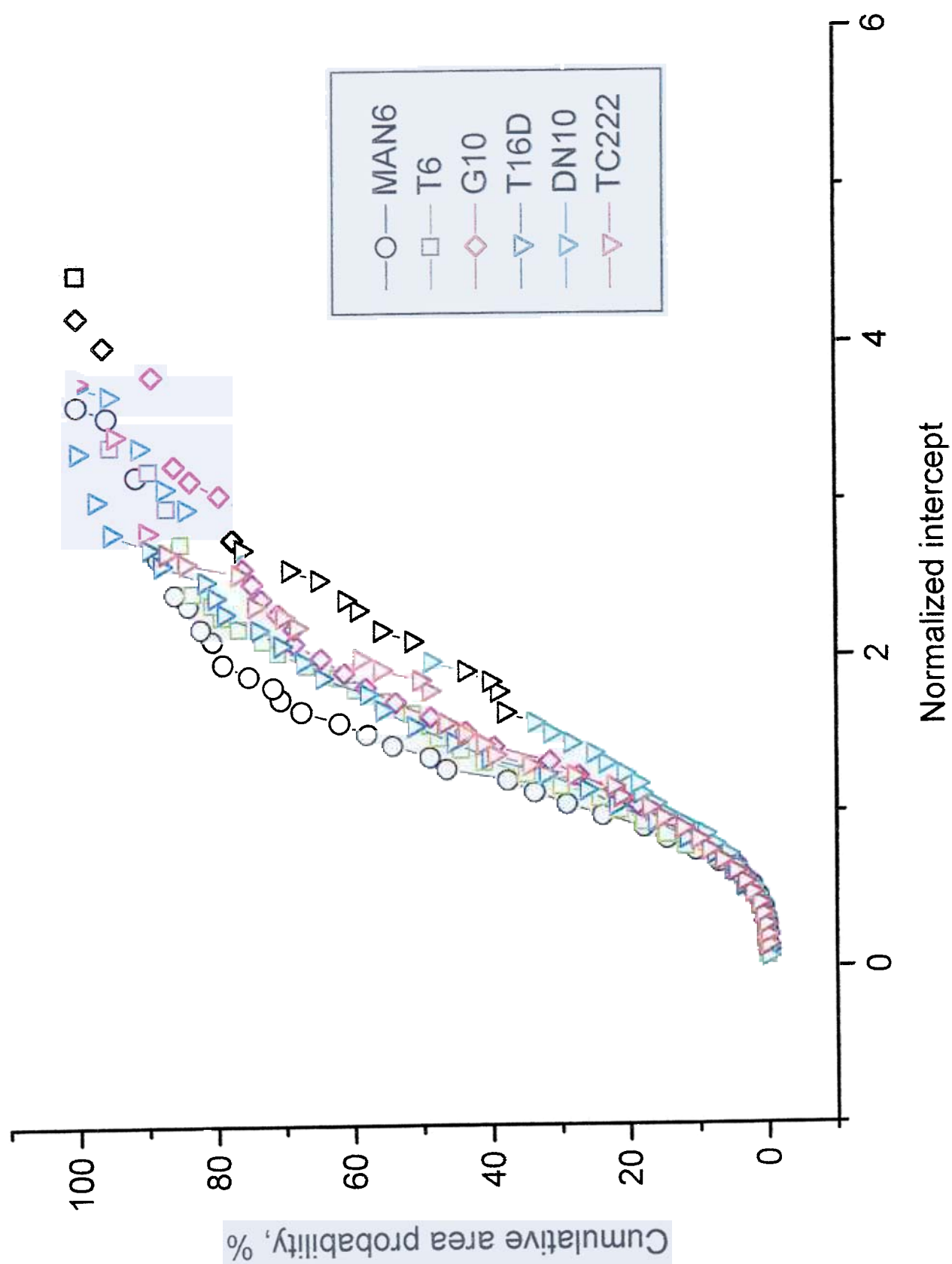


Fig 48 Cumulative size distributions for MAN6, T6, G10, T16D, DN10 and TC222

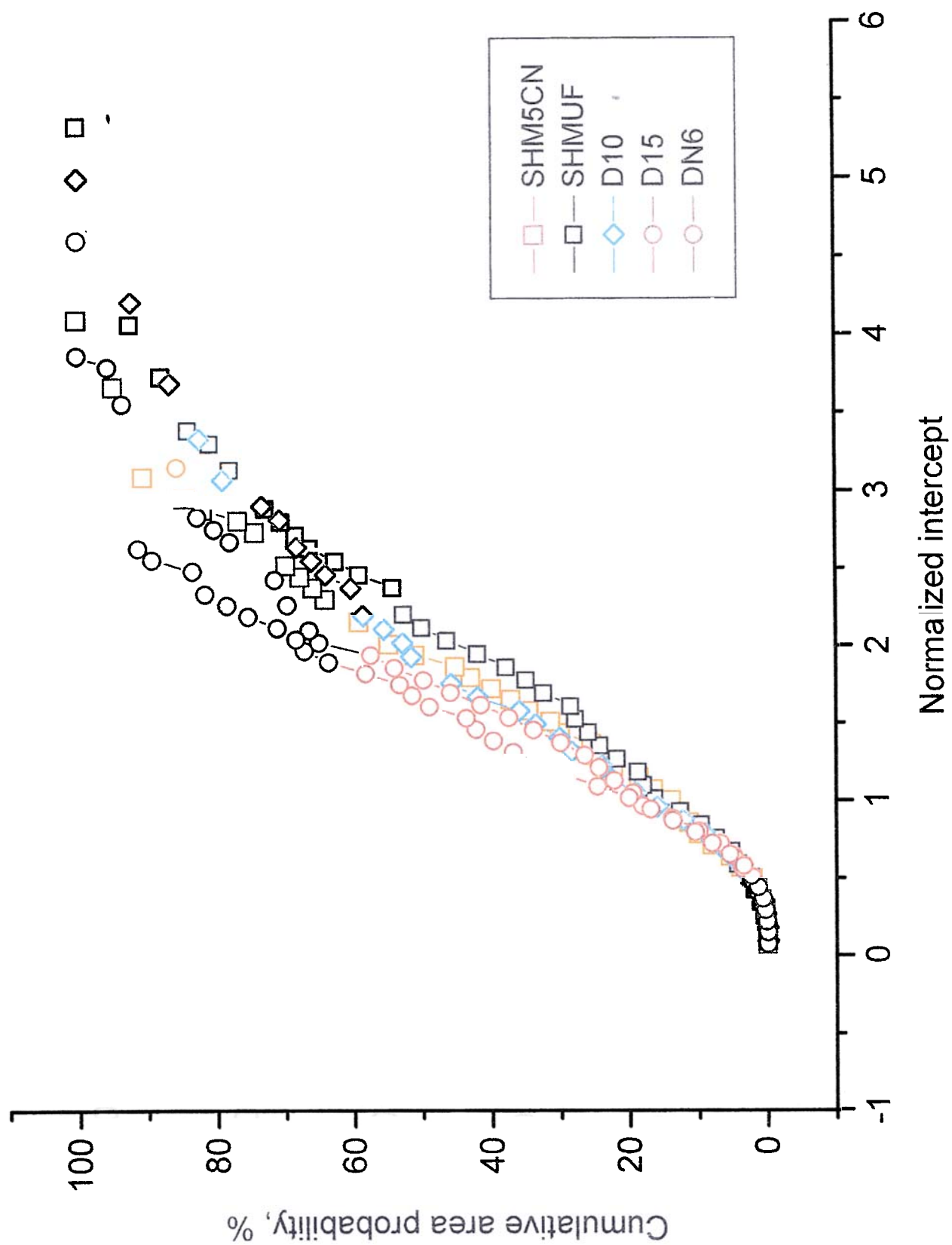


Fig 49 Cumulative size distributions for MAN10, CW15C, UC9, N6, N15 and T25D

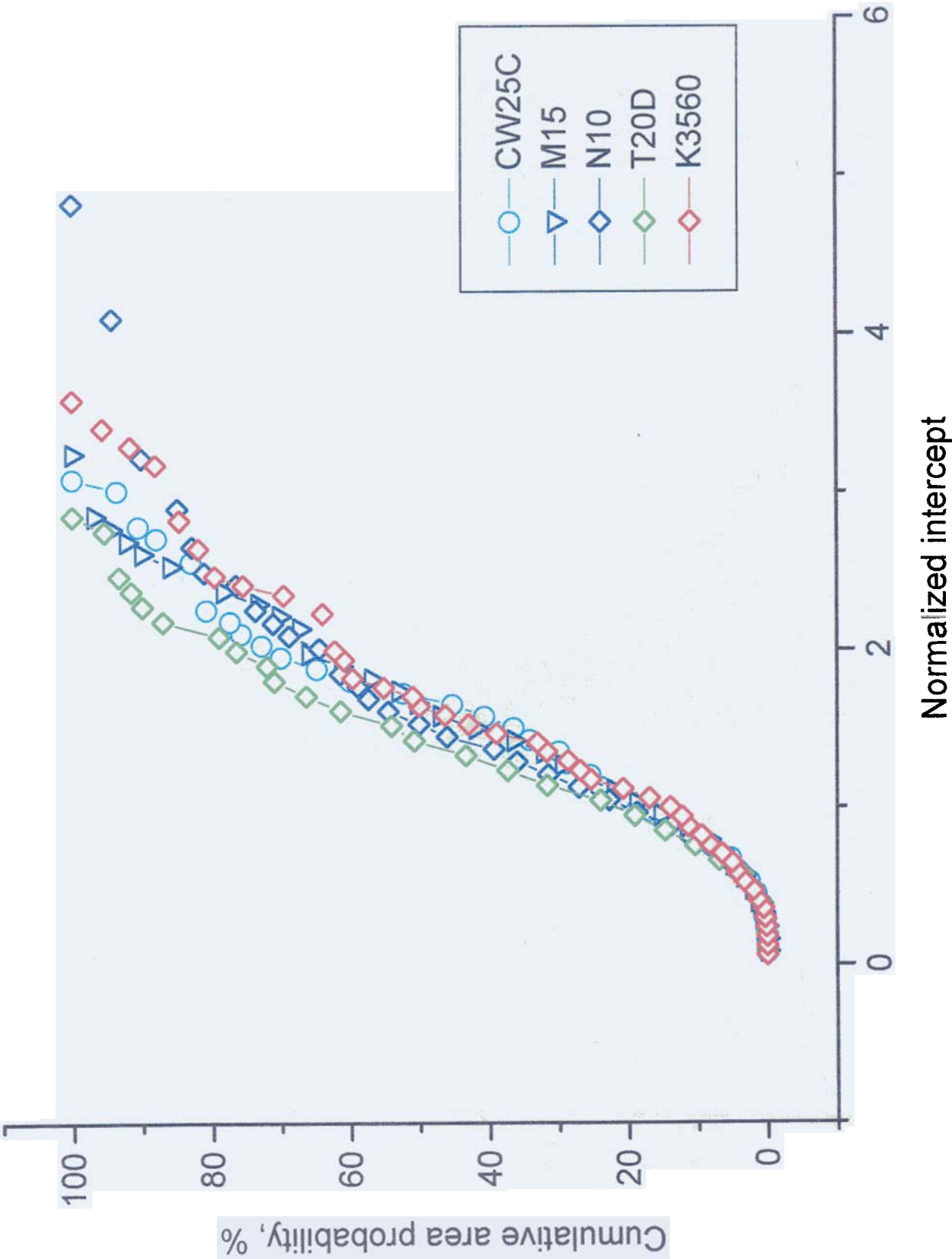


Fig 50 Cumulative size distributions for CW25C, M15, N10, T20D and K3560

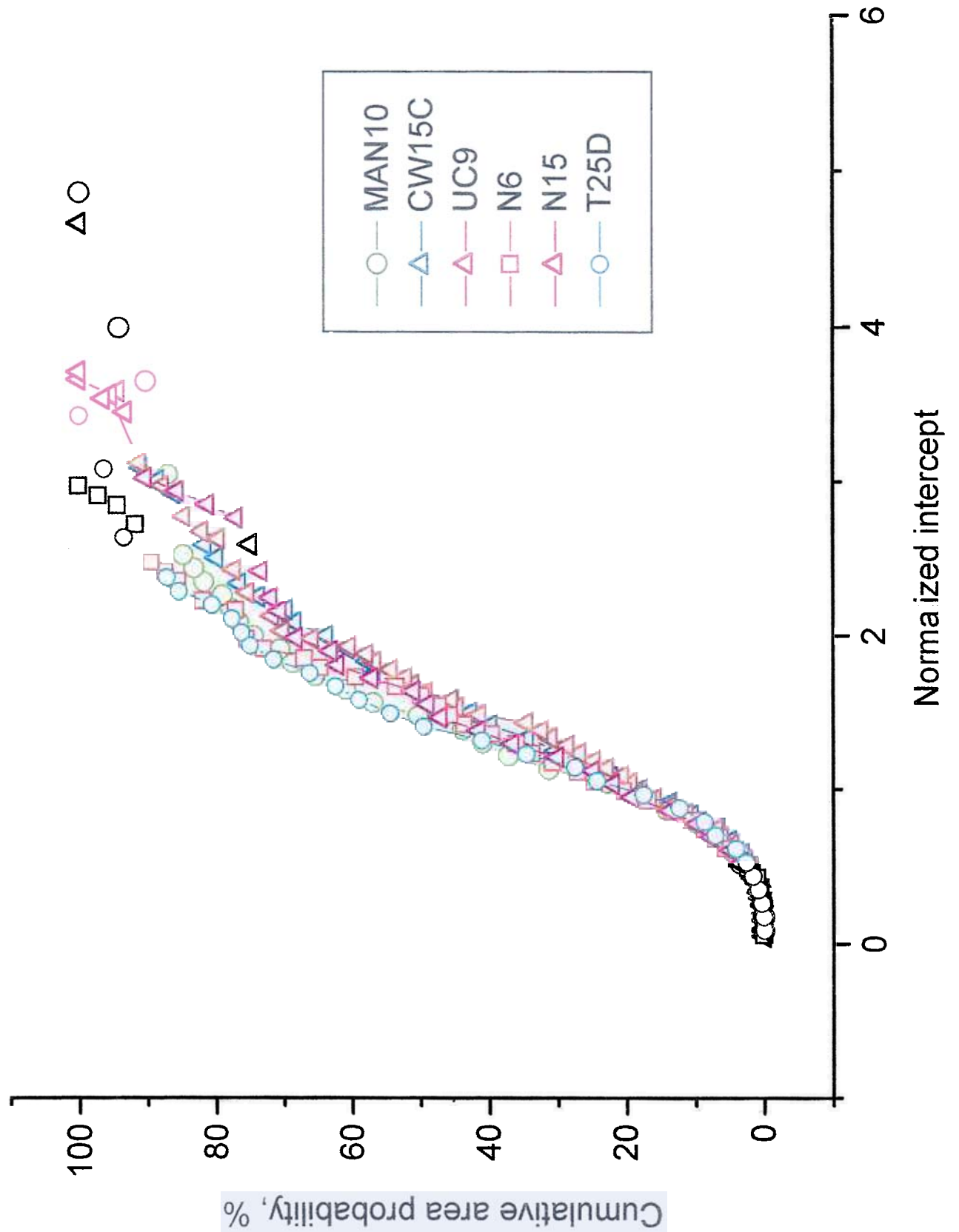


Fig 51 Cumulative size distributions for CW15F, CW20C, CWN8, T, G15 and TC6

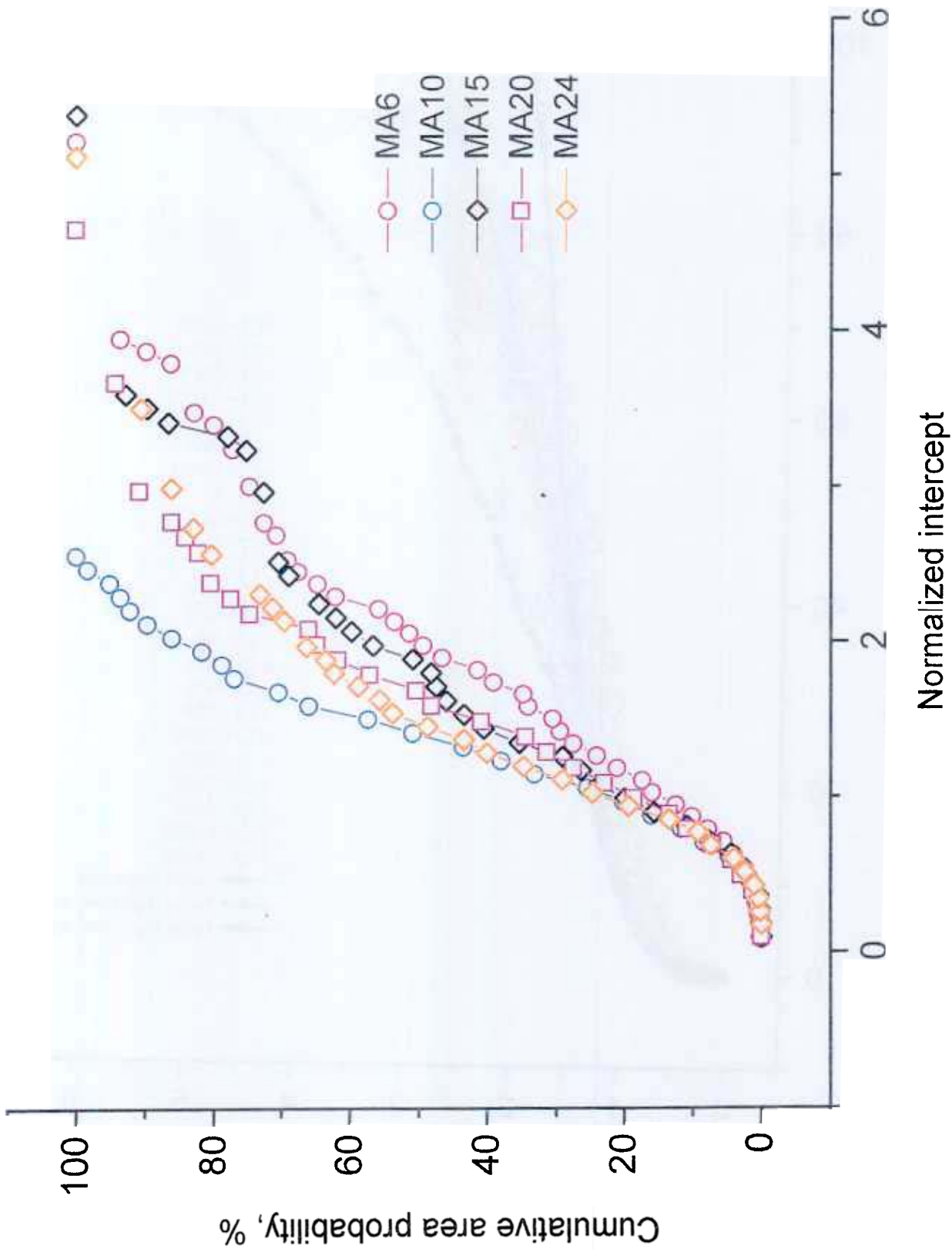


Fig 52 Cumulative size distributions for SHM5CN, SHMUF, D10, D15 and DN6

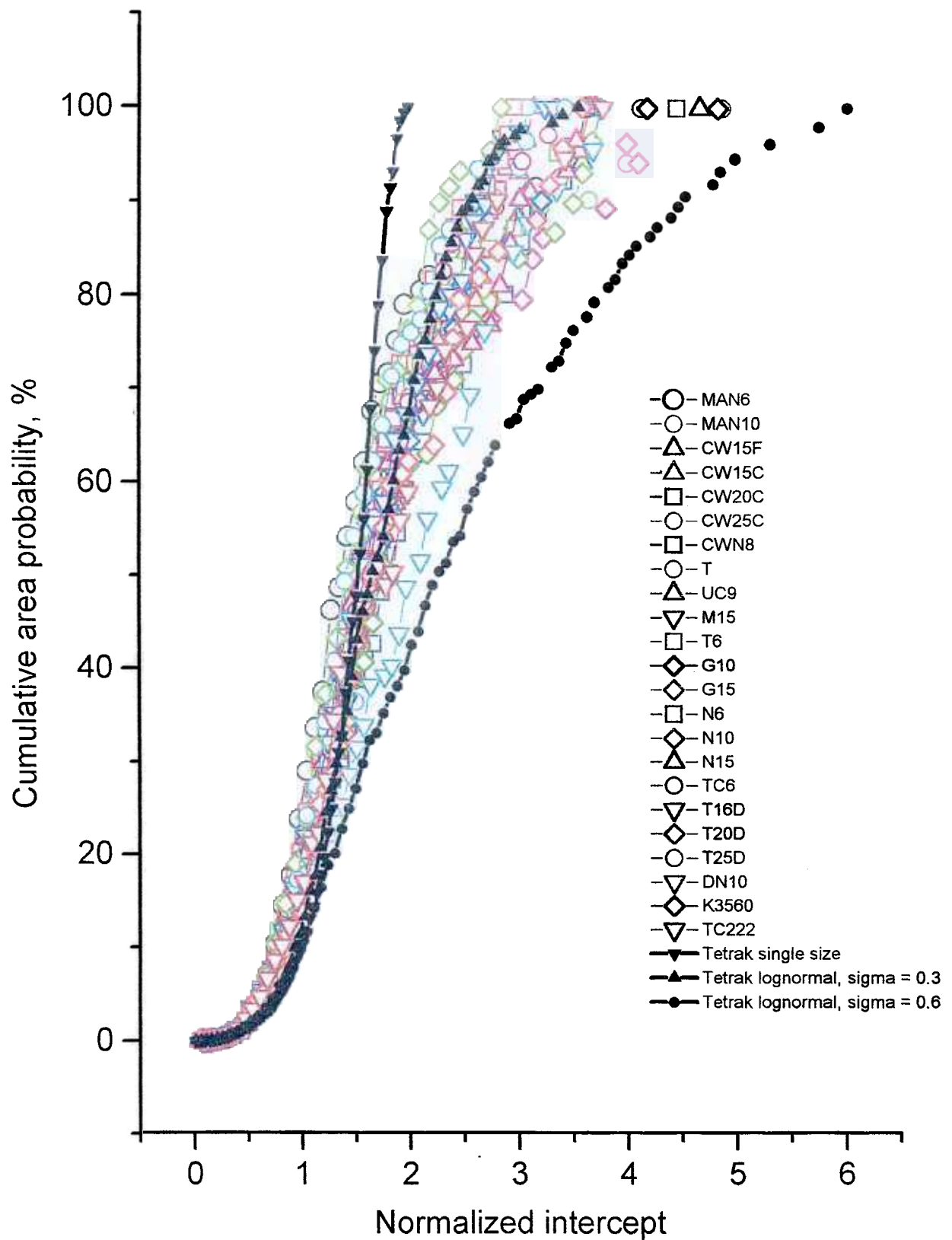


Fig 53 Cumulative size distributions compared with model predictions for a tetrakaidecahedron

Property Map

Abrasion / Hardness

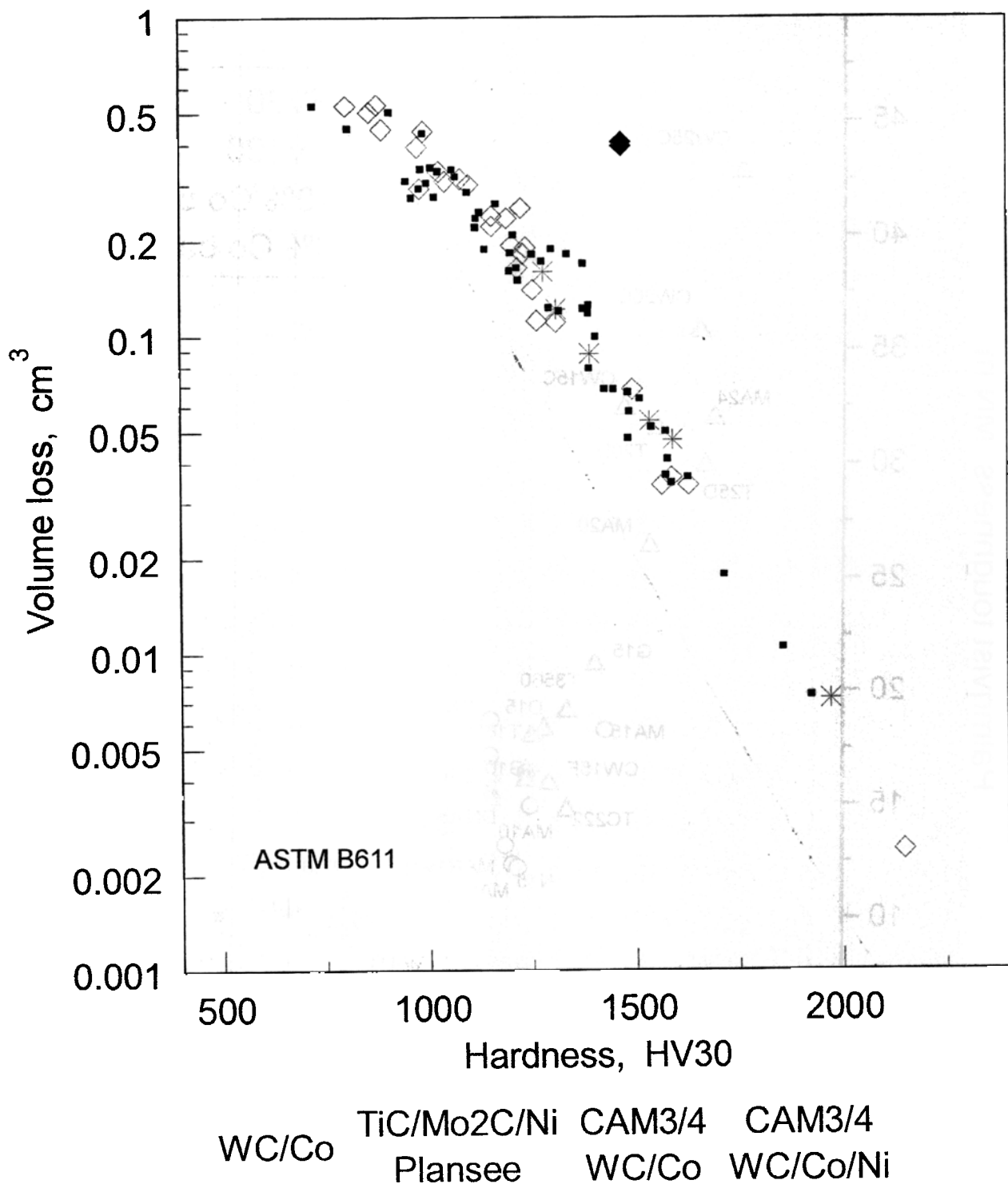


Fig 54 Abrasion test results

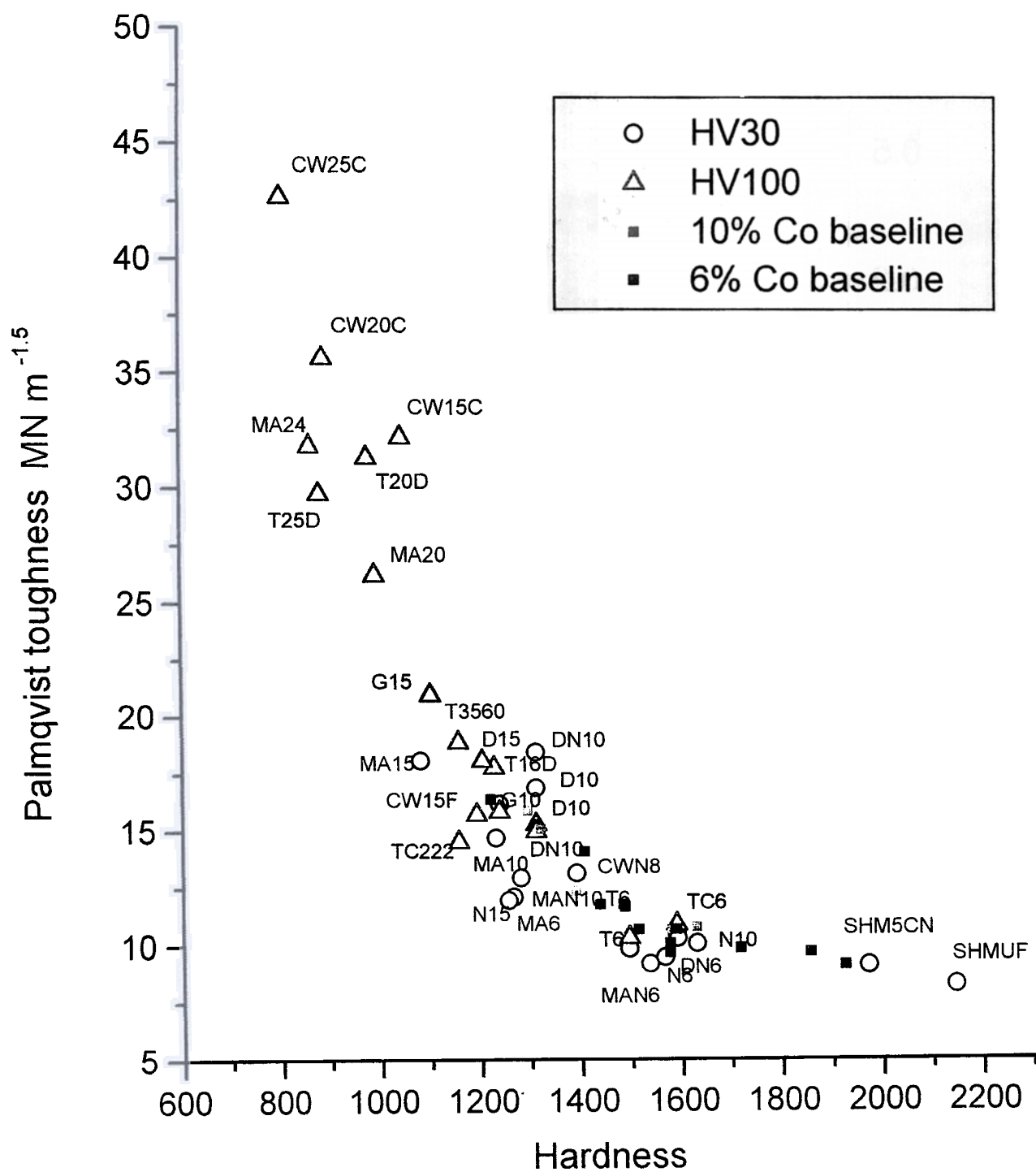


Fig 55 Palmqvist test results compared with previous data

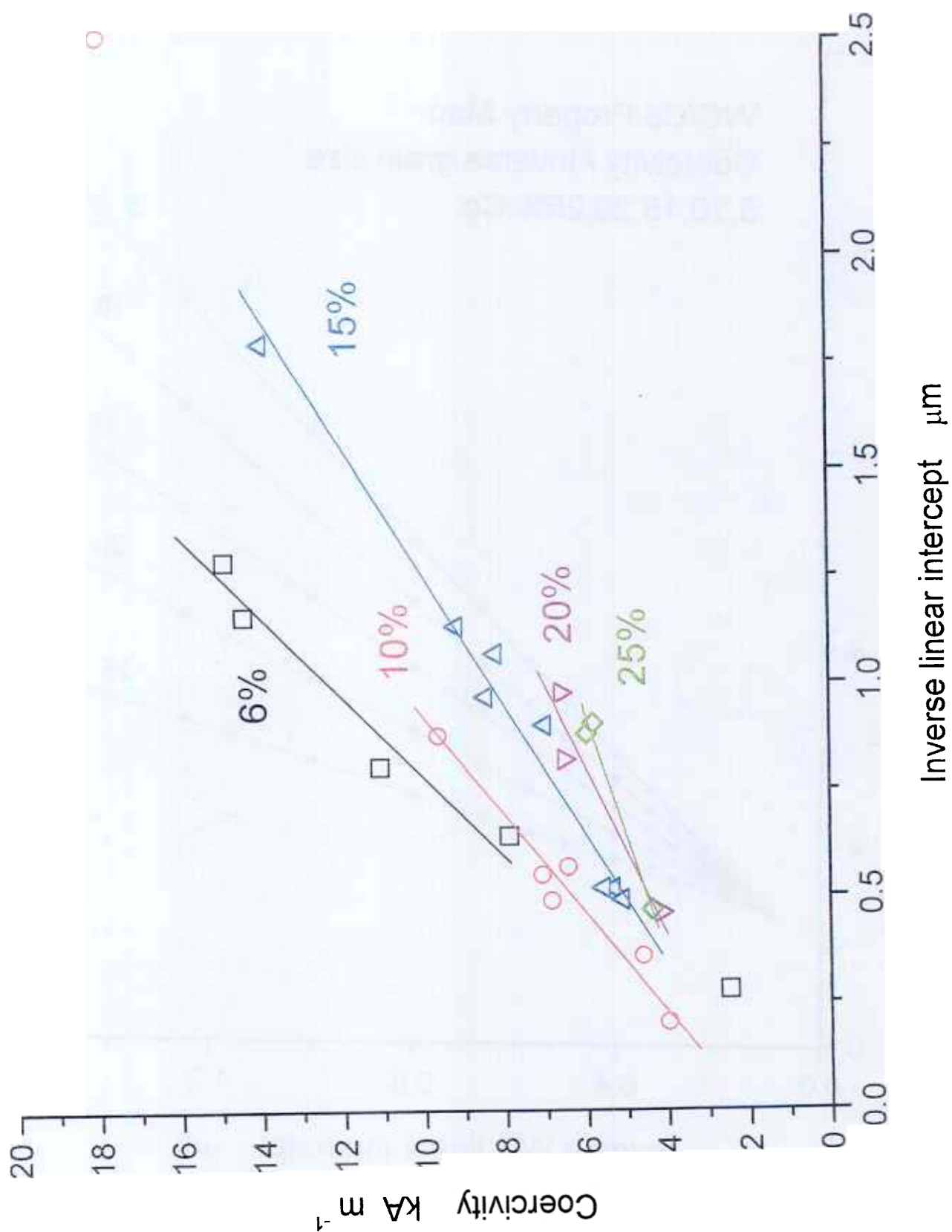


Fig 56 Coercivity plotted against inverse grain size

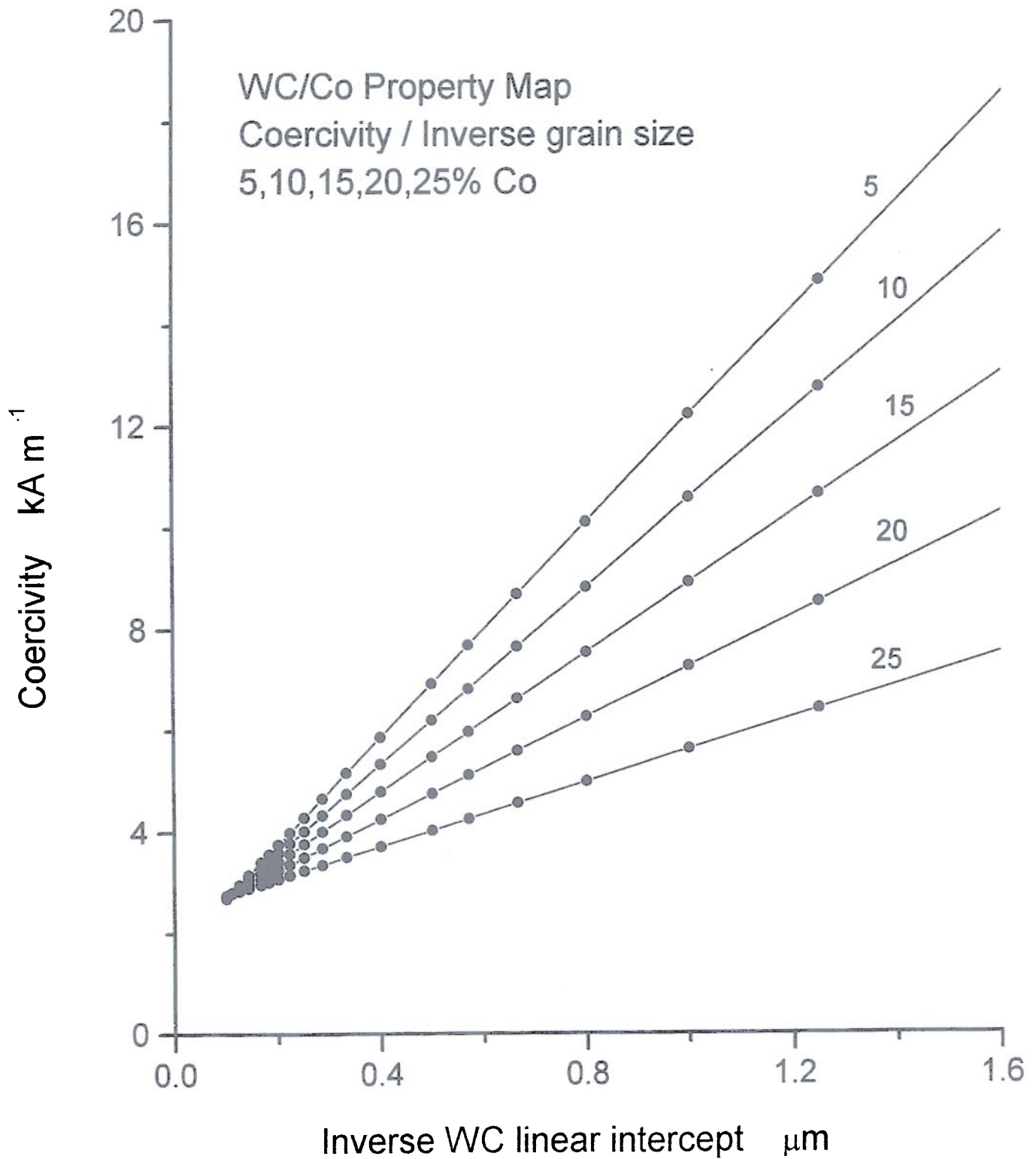


Fig 57 Coercivity/inverse grain size property map

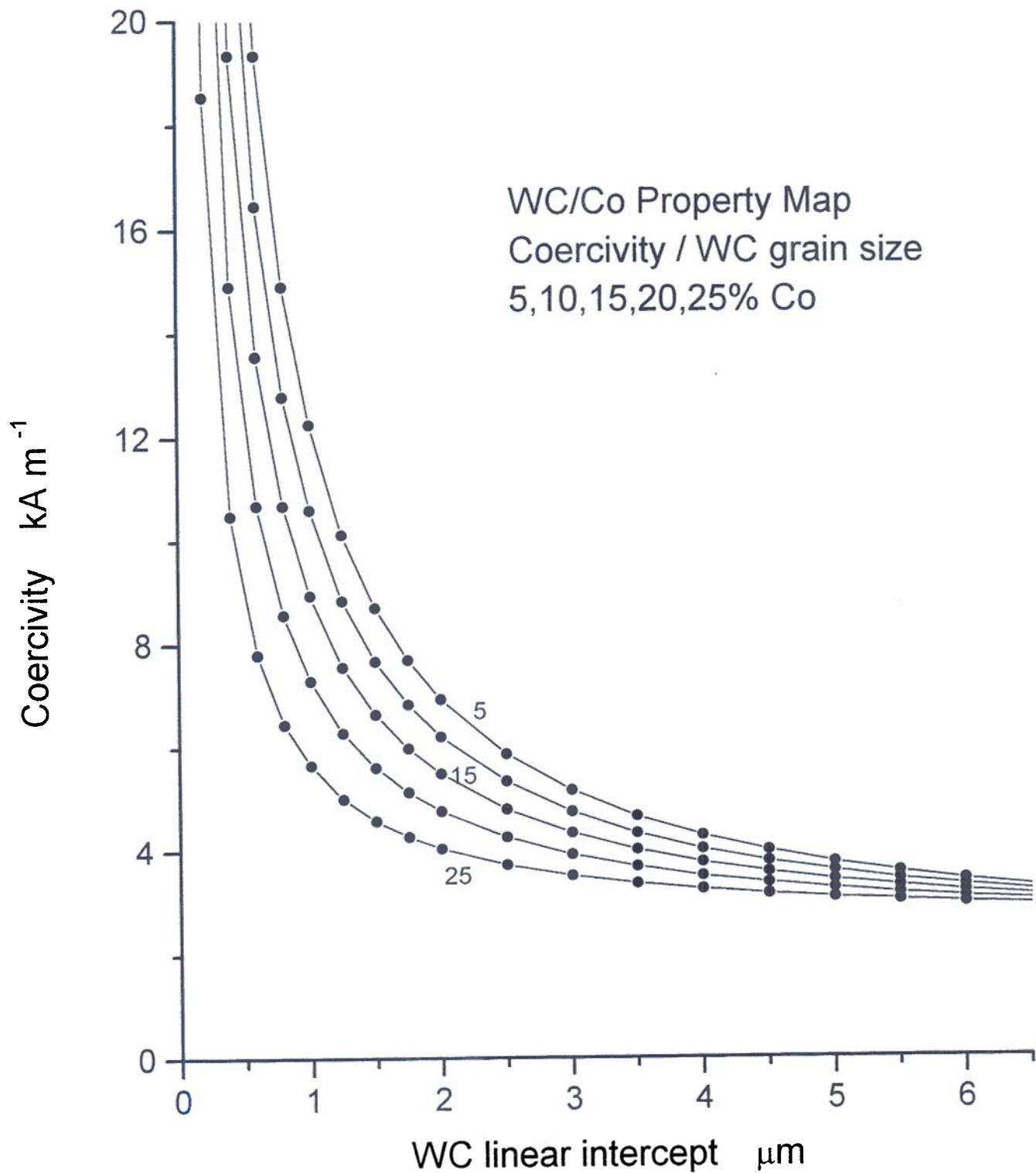


Fig 58 Coercivity/grain size property map

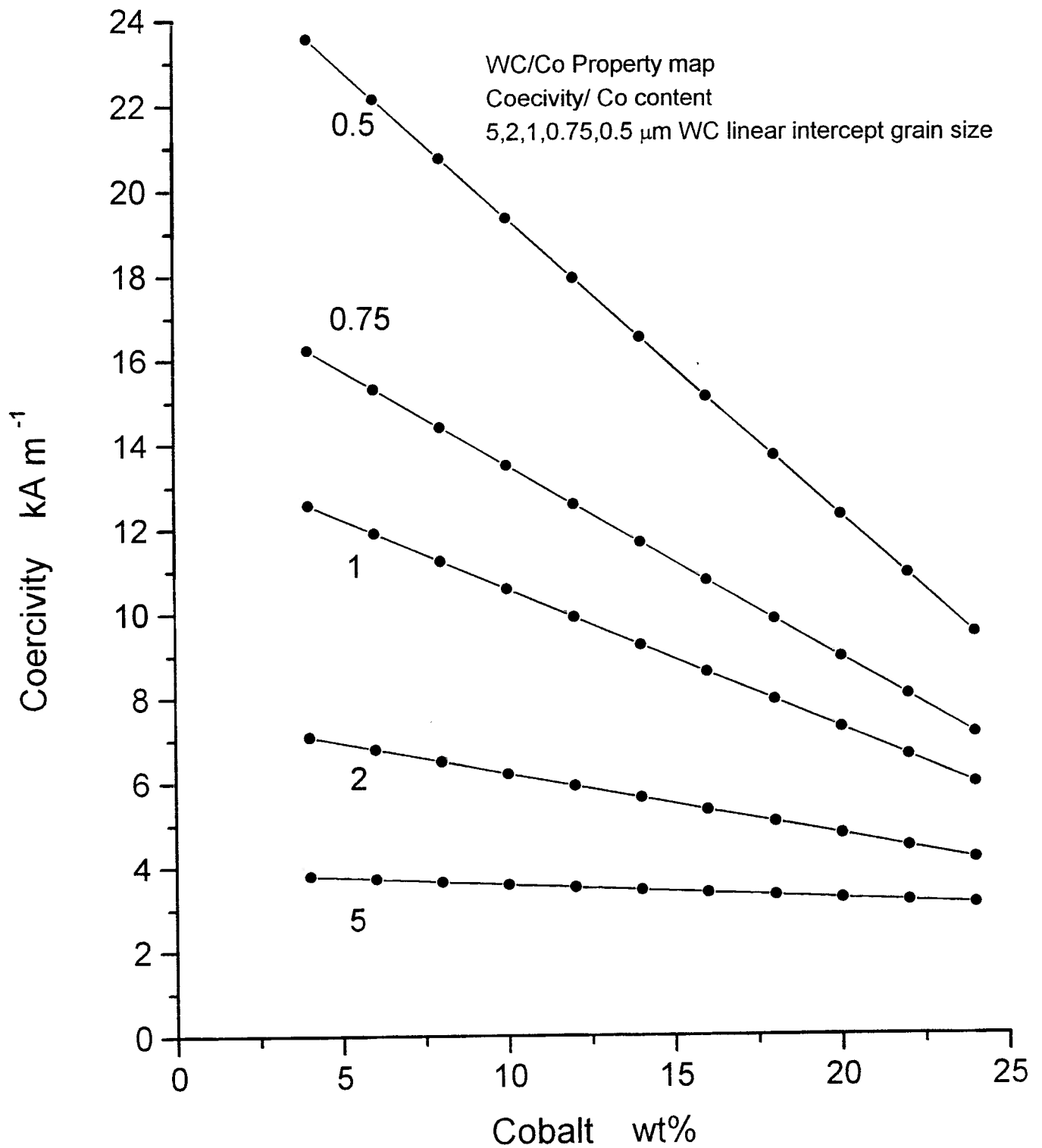


Fig 59 Coercivity/Co content property map

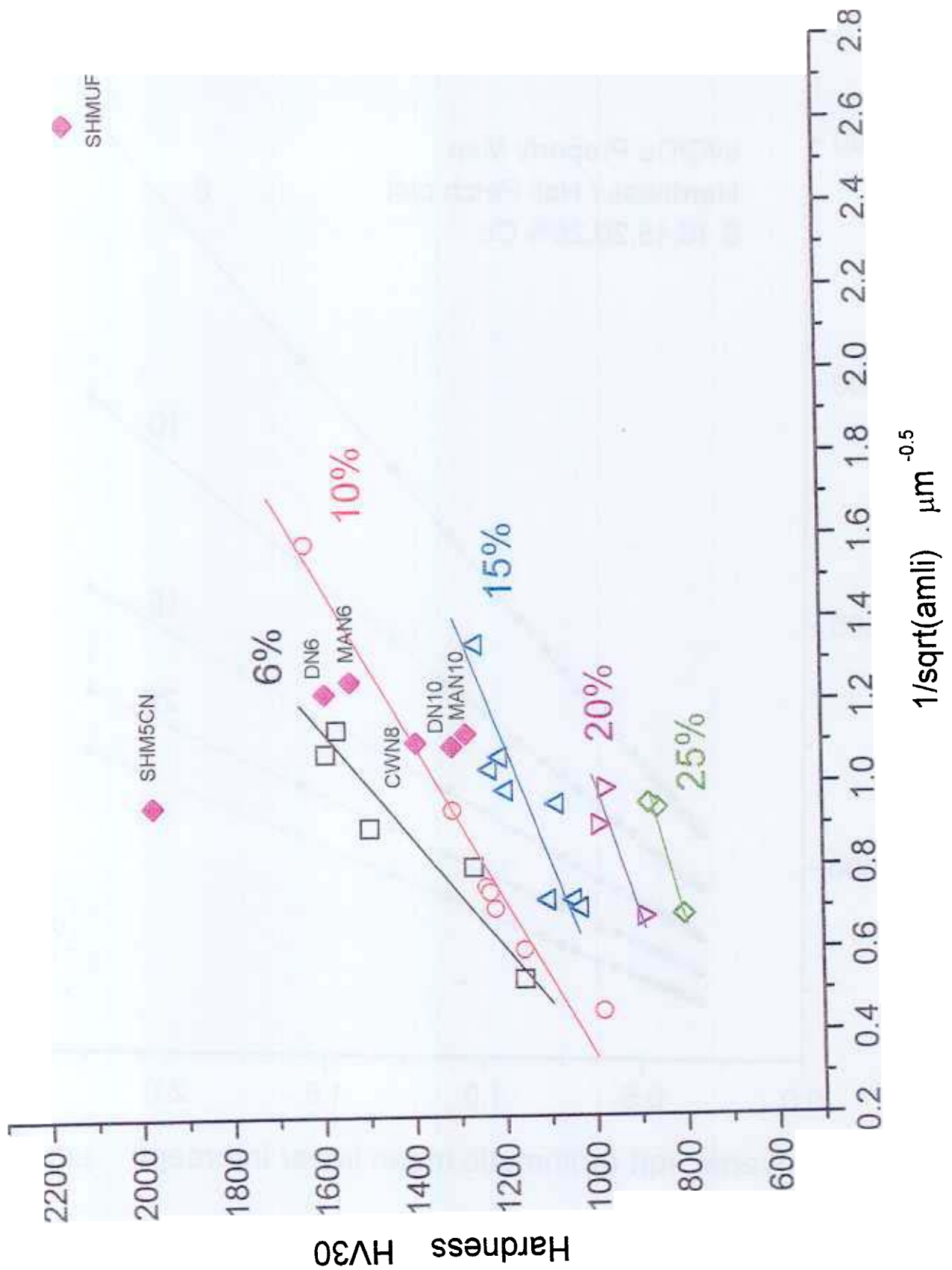


Fig 60 Hardness/inverse square root grain size data for CAM3/4 materials

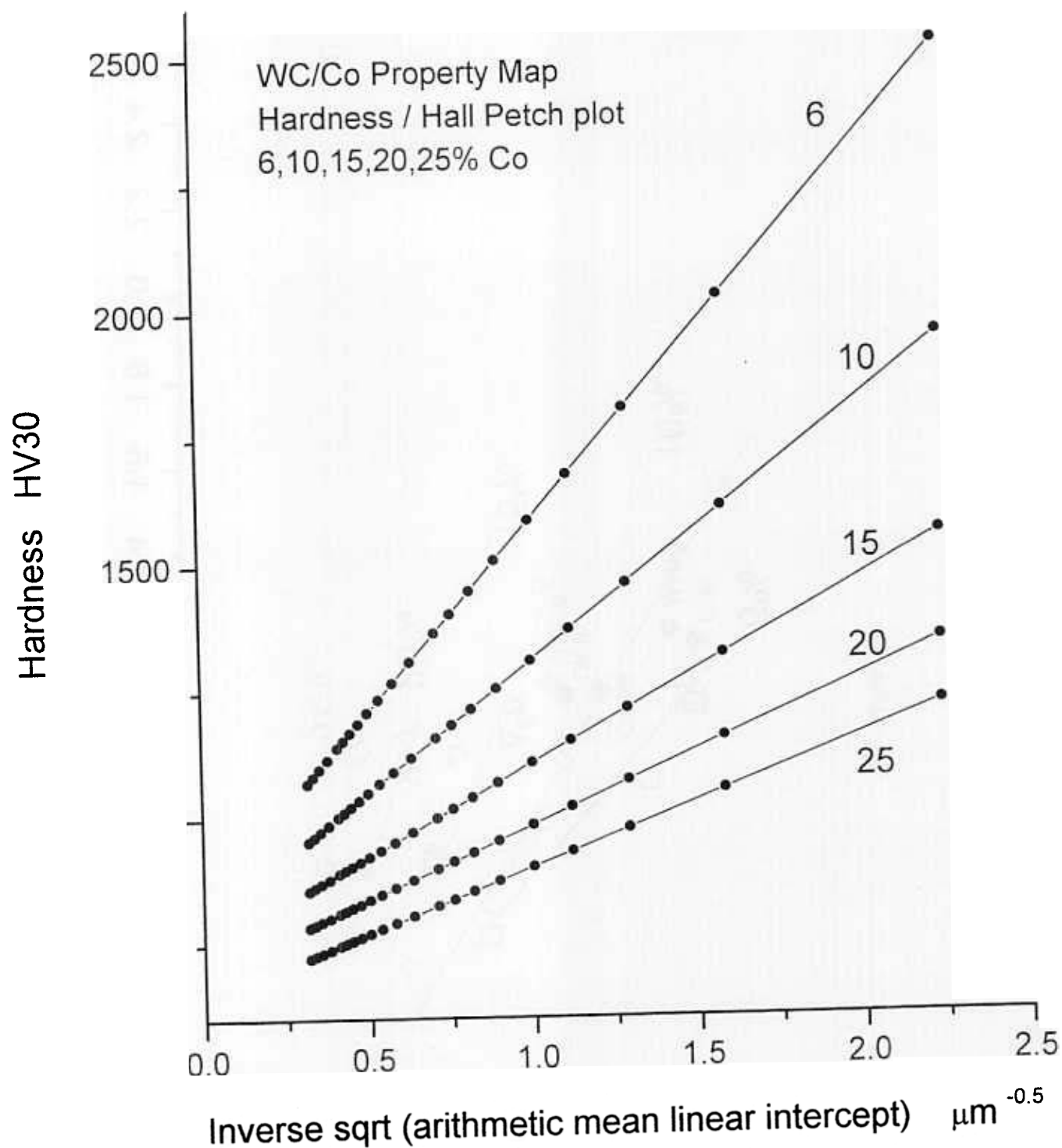


Fig 61 Hardness/inverse square root grain size property map

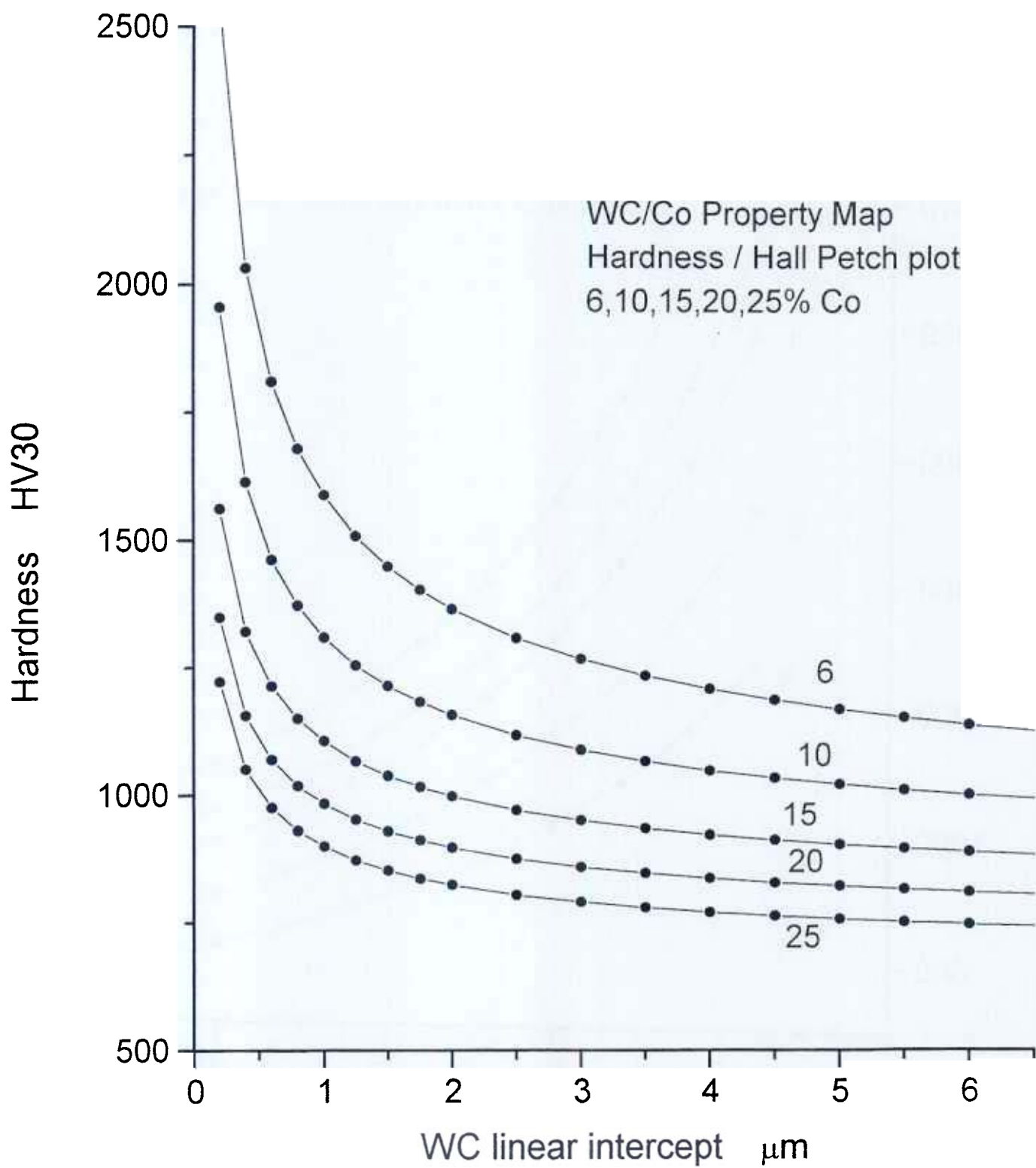


Fig 62 Hardness/grain size property map

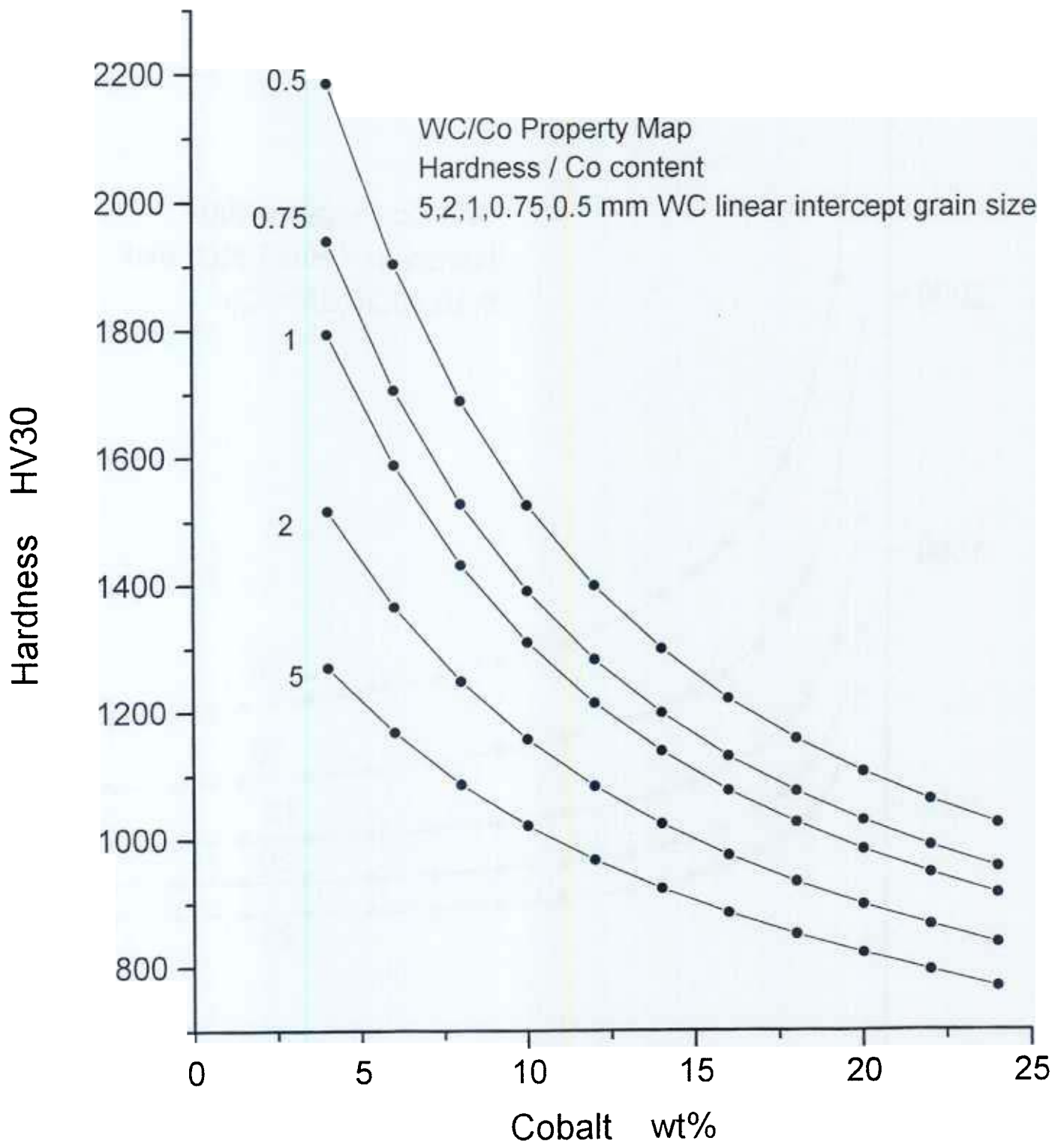


Fig 63 Hardness/Co content property map

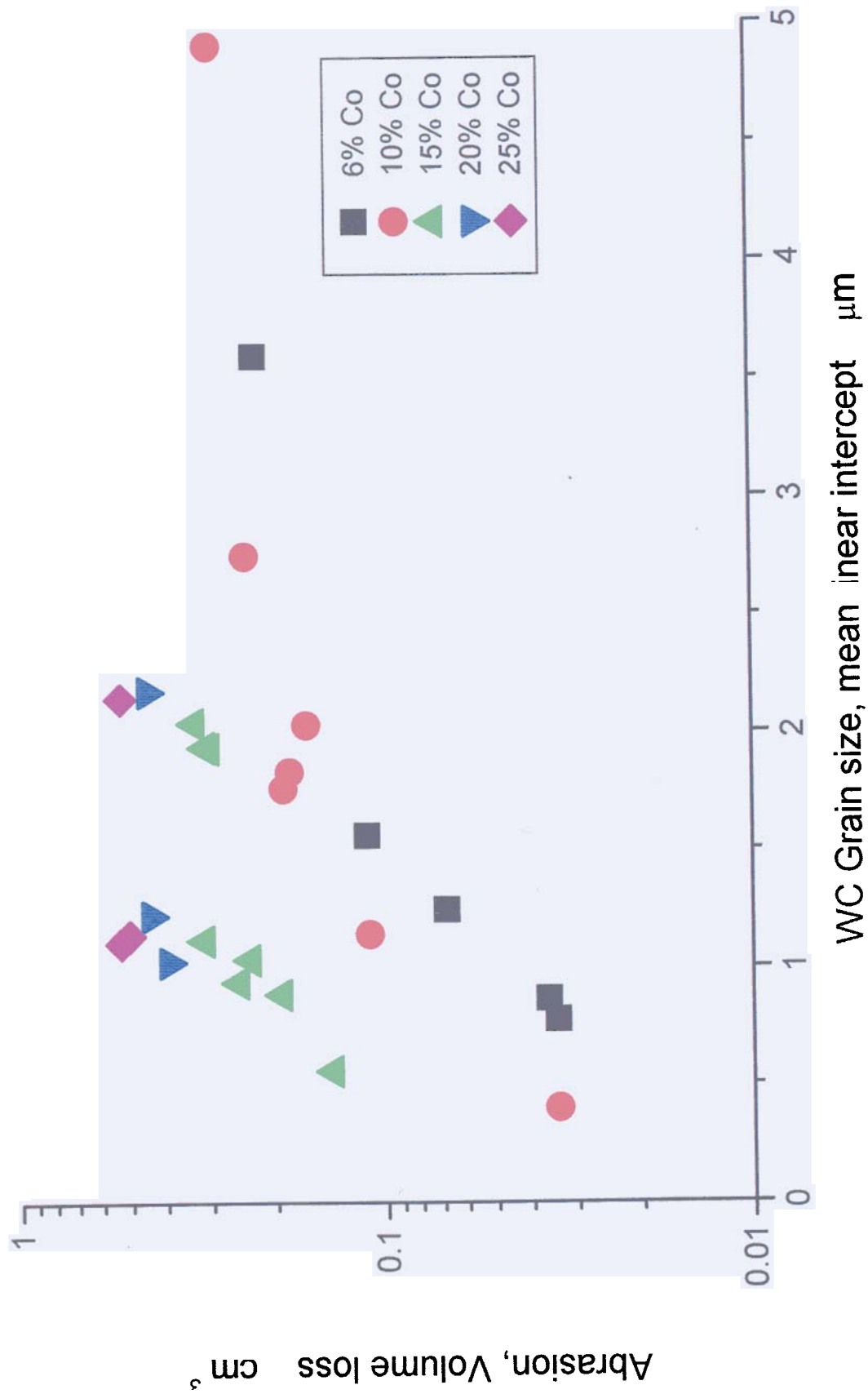


Fig 64 Abrasion (volume loss)/grain size data for CAM3/4 materials

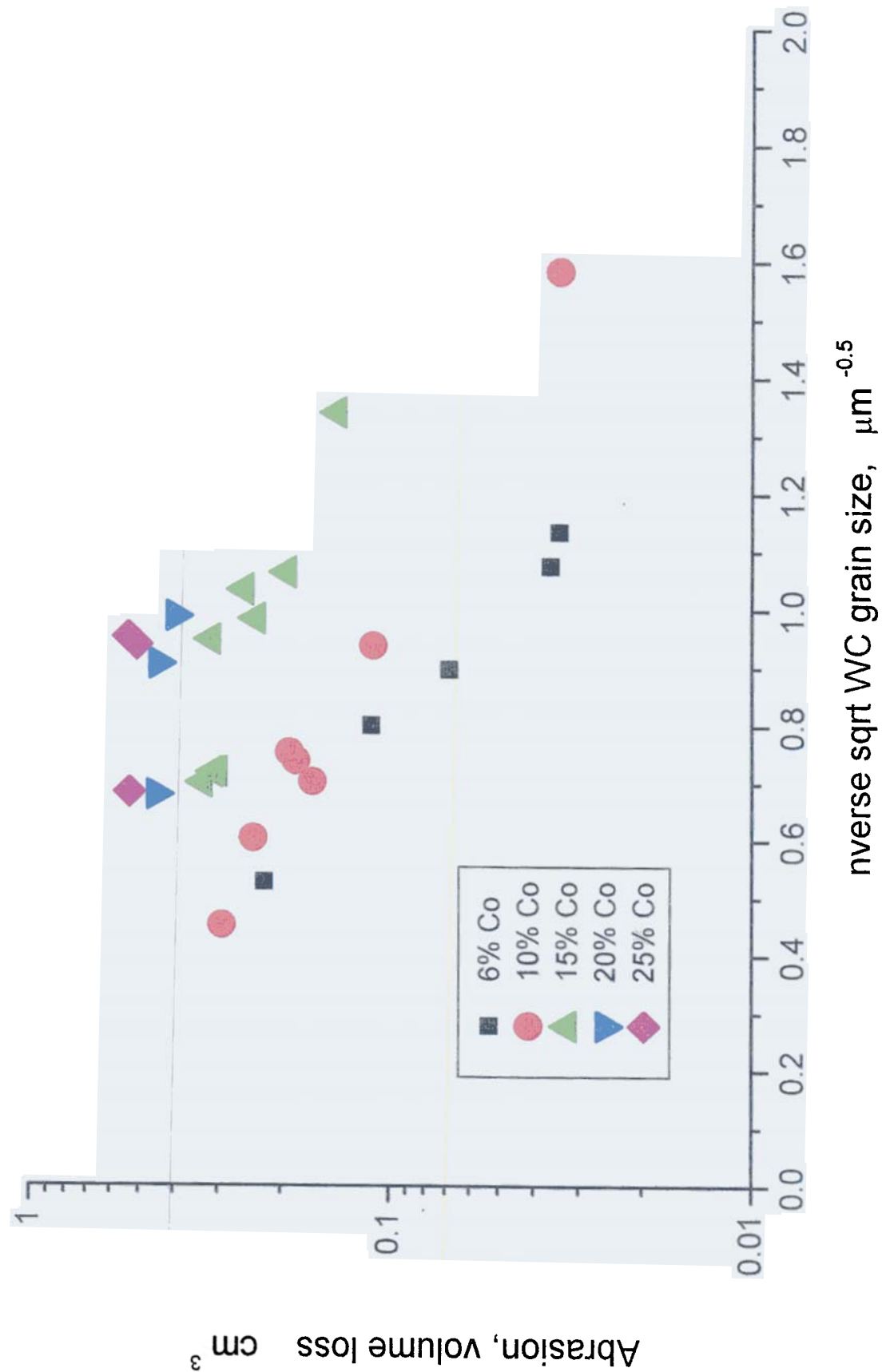


Fig 65 Abrasion (volume loss)/inverse square root grain size for CAM3/4 materials

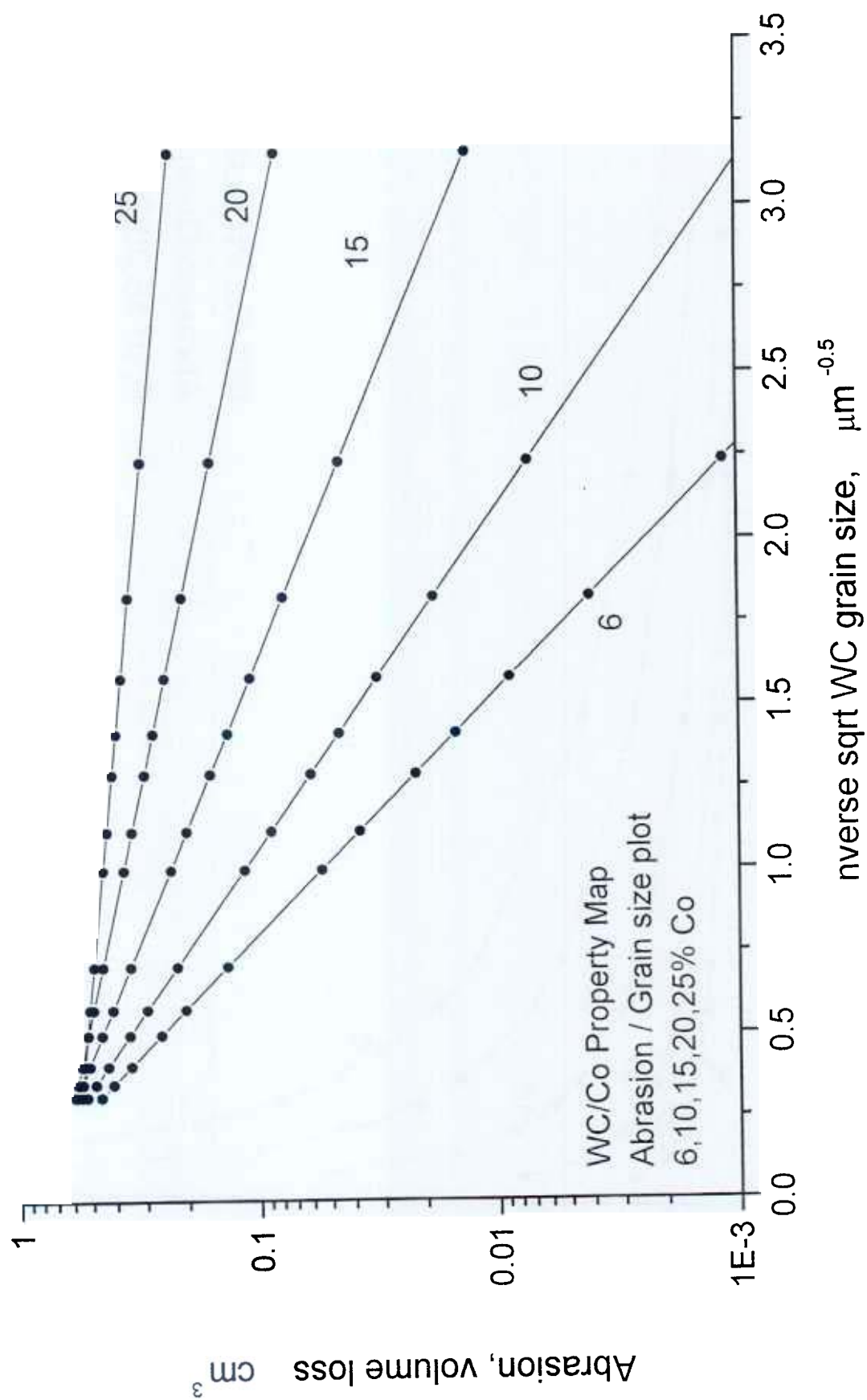


Fig 66 Abrasion (volume loss)/inverse square root grain size property map

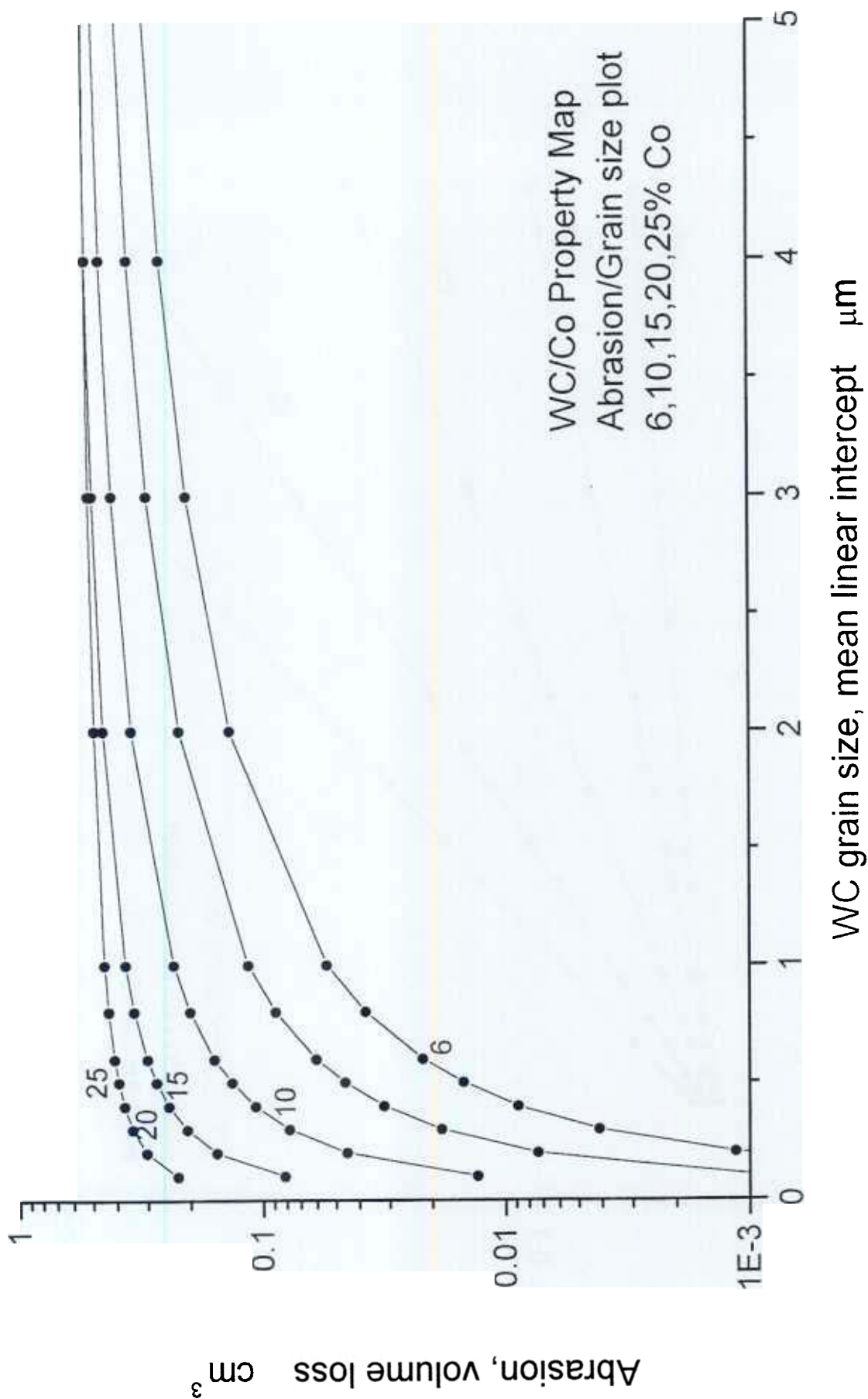


Fig 67 Abrasion (volume loss)/grain size property map

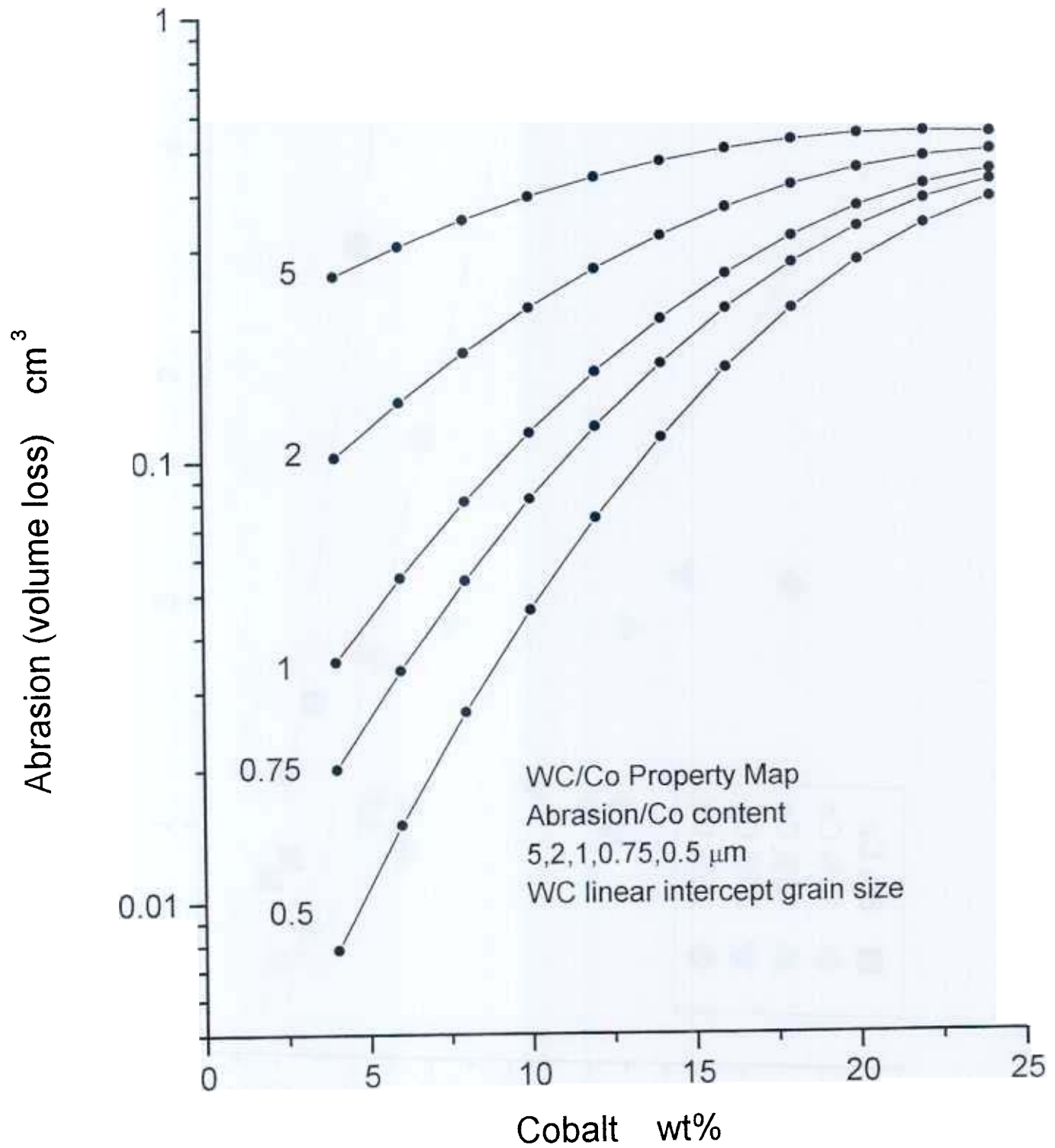


Fig 68 Abrasion (volume loss)/Co content property map

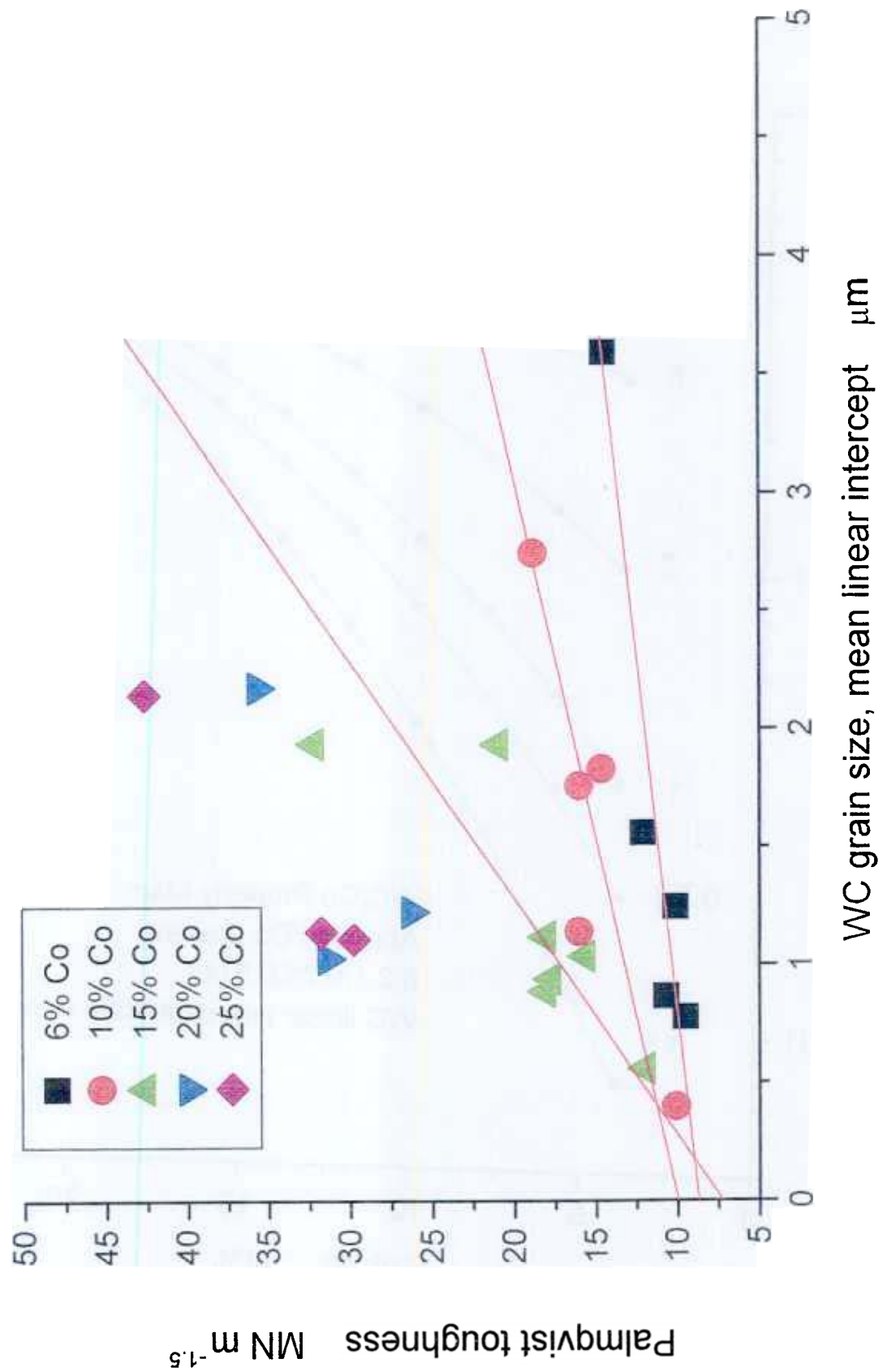


Fig 69 Palmqvist toughness data plotted against grain size for the CAM3/4 hardmetals

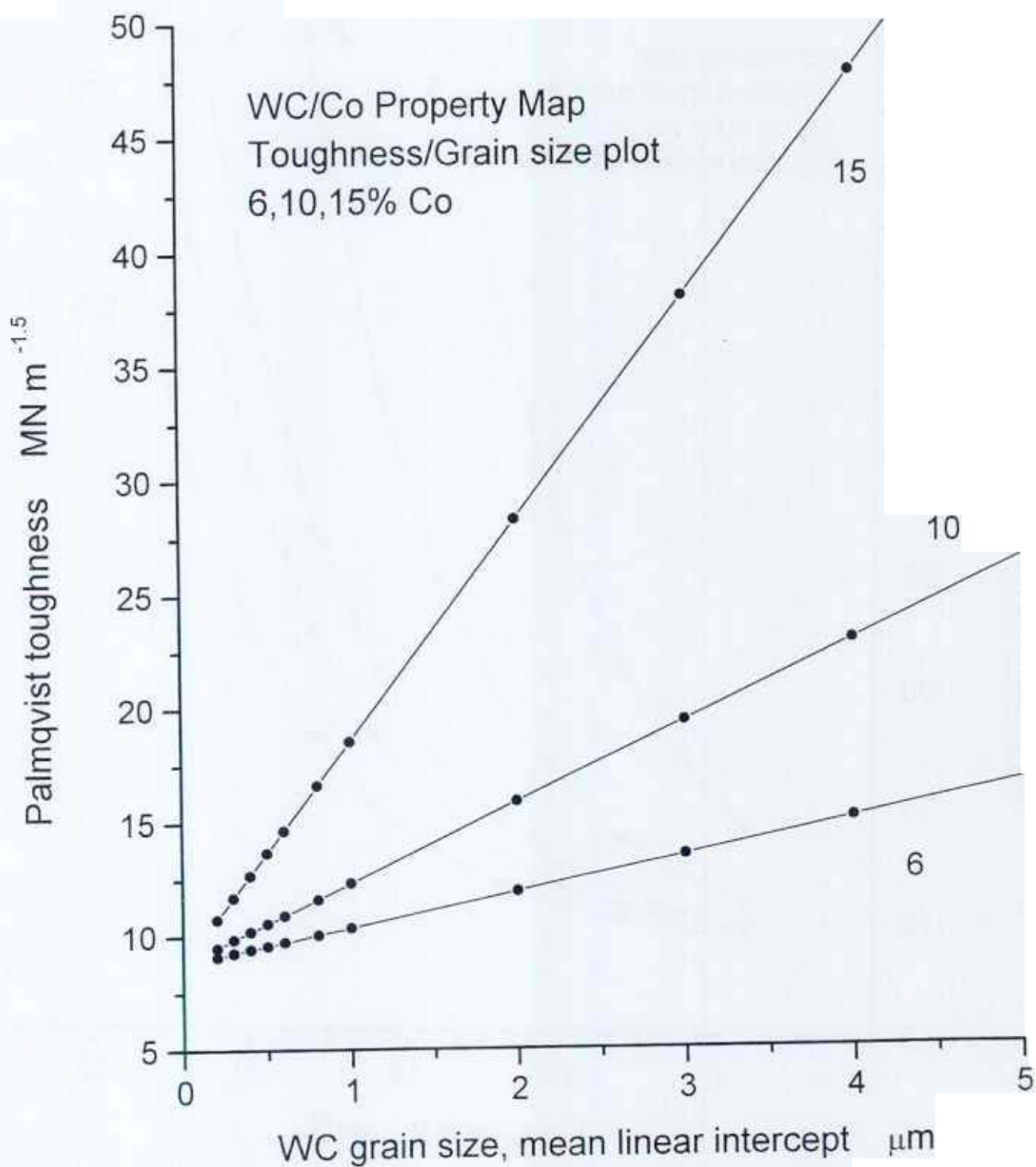


Fig 70 Palmqvist toughness/grain size property map

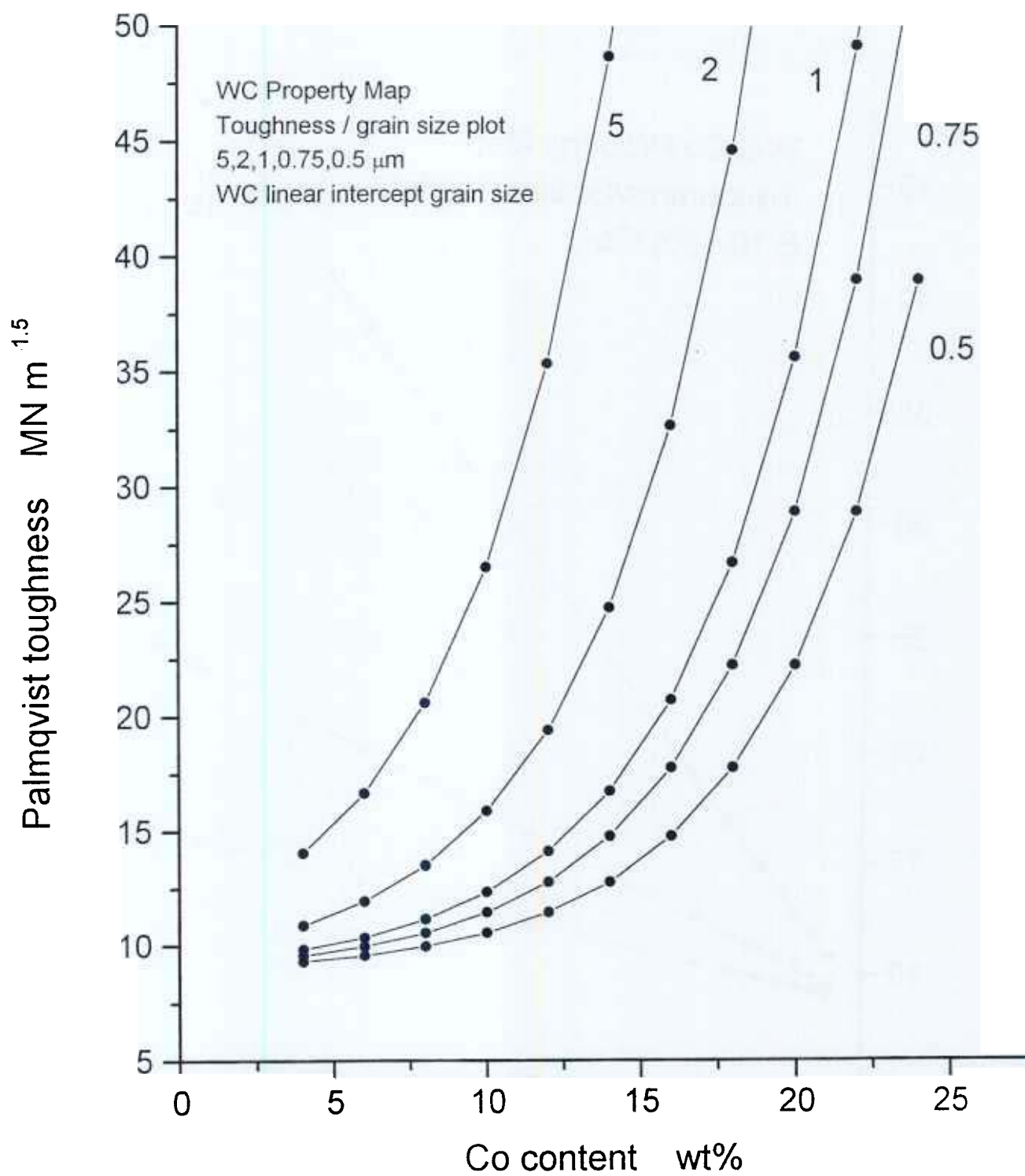


Fig 71 Palmqvist toughness/Co content property map

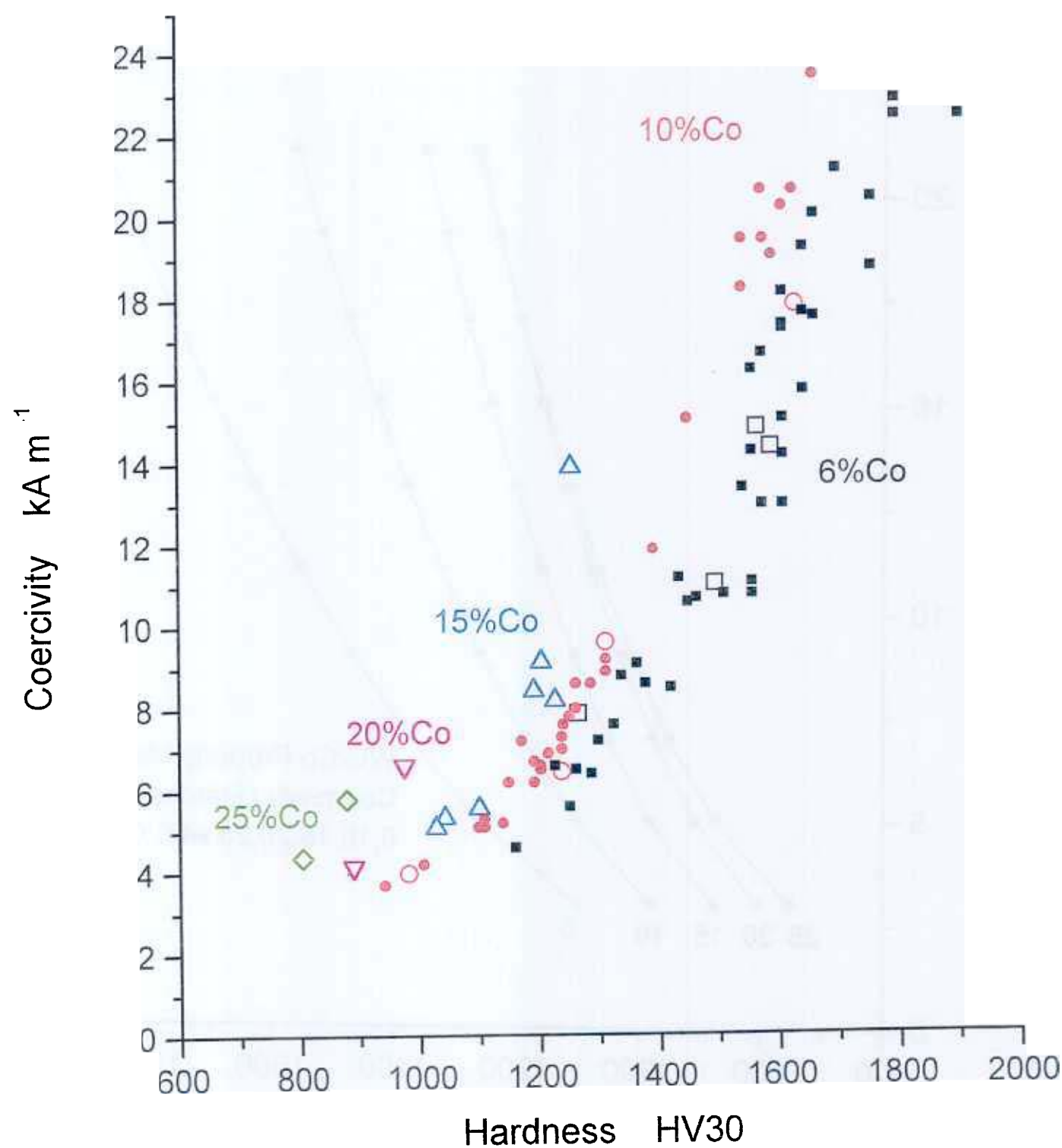


Fig 72 Coercivity/Hardness measurements

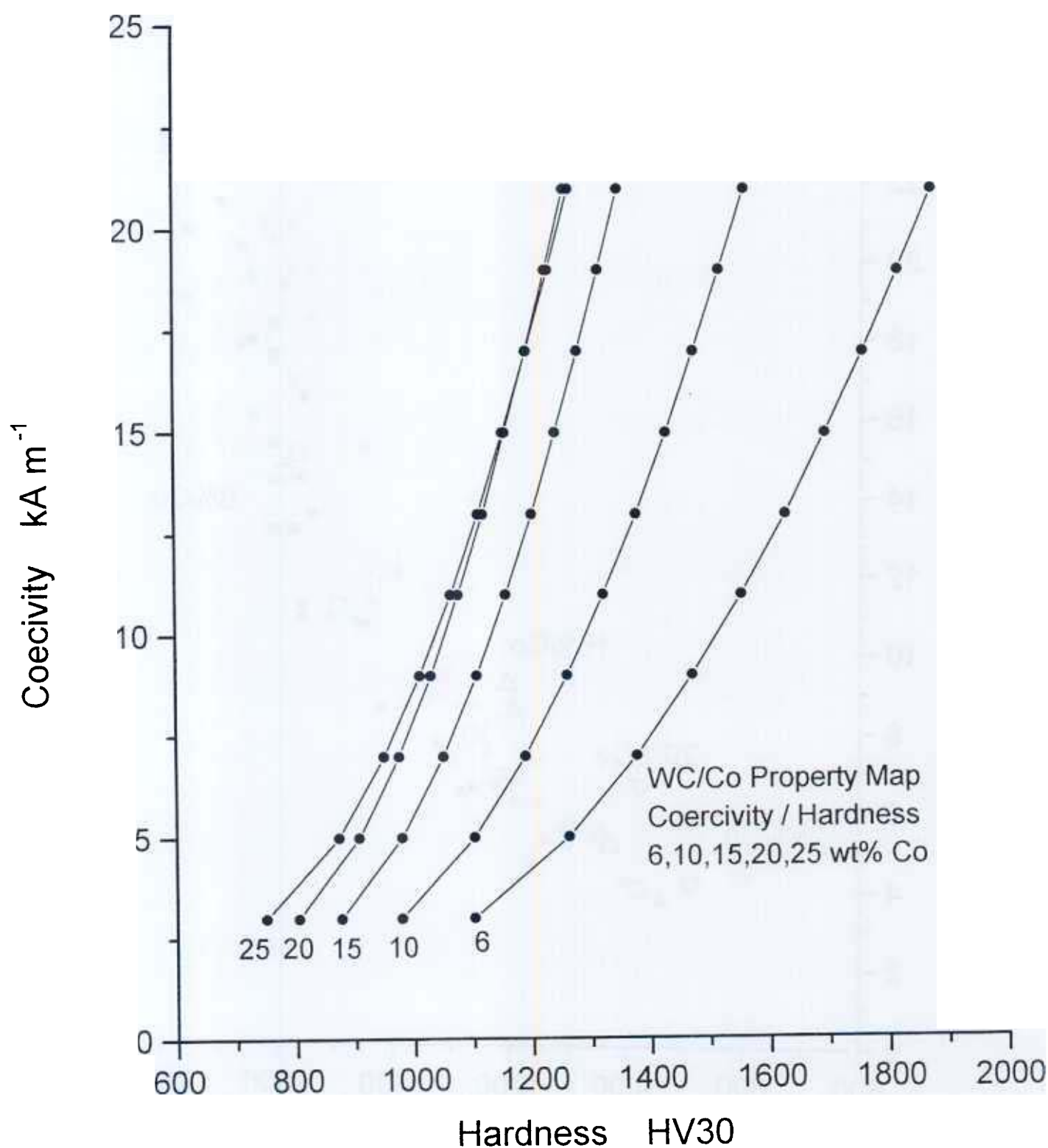


Fig 73 Coercivity/Hardness property map

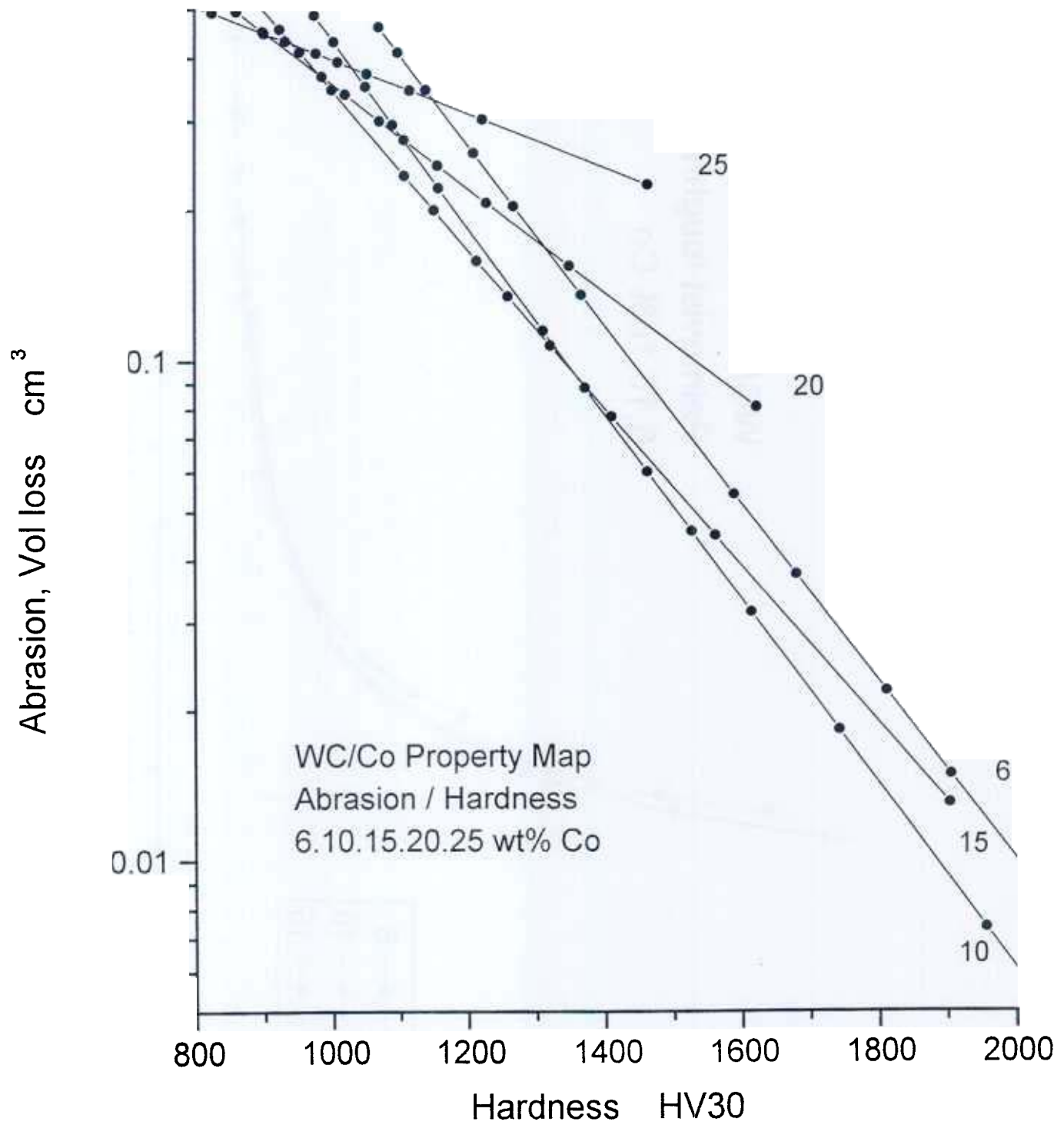


Fig 74 Abrasion (volume loss)/Hardness property map

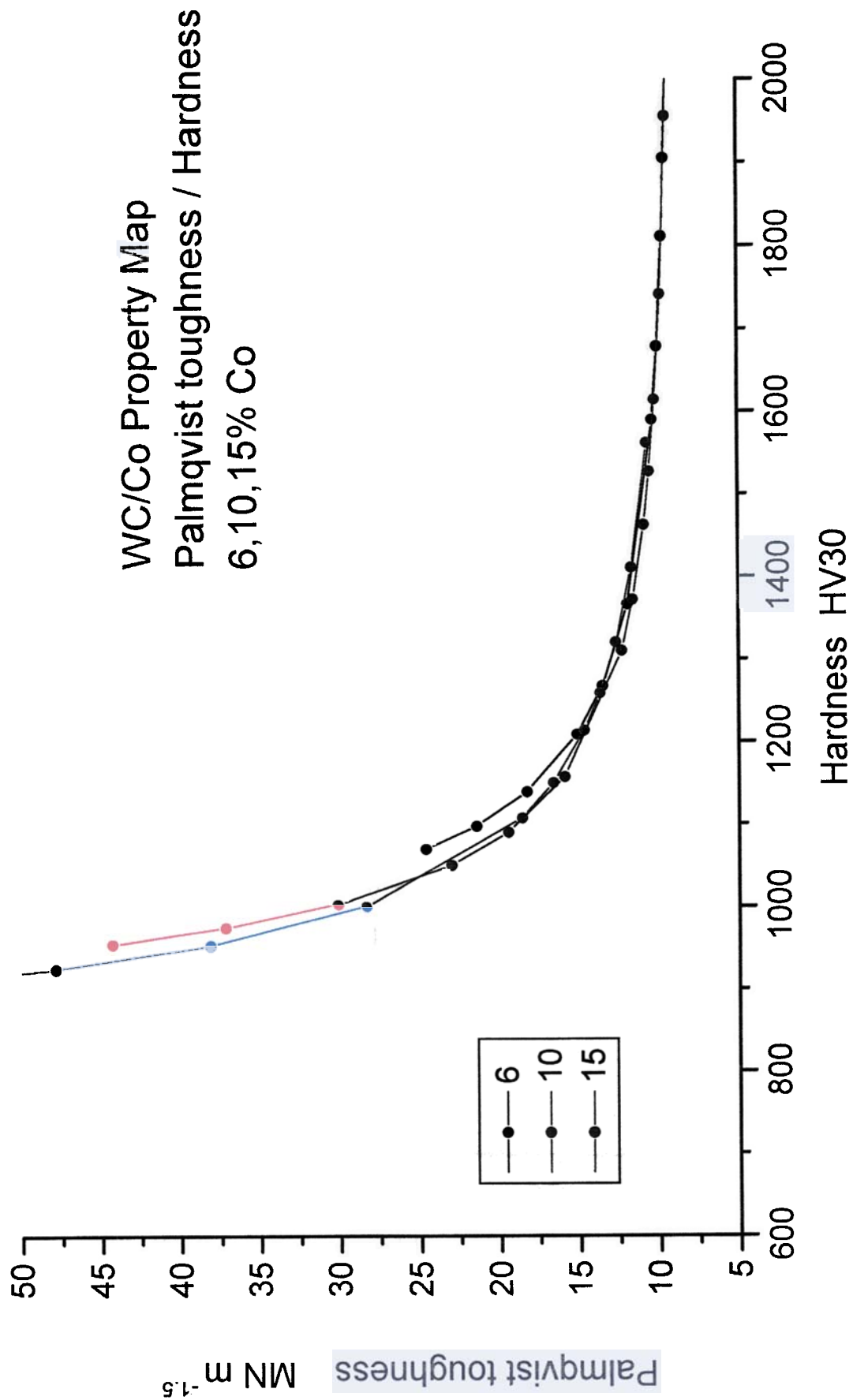


Fig 75 Toughness (Palmqvist)/Hardness property map

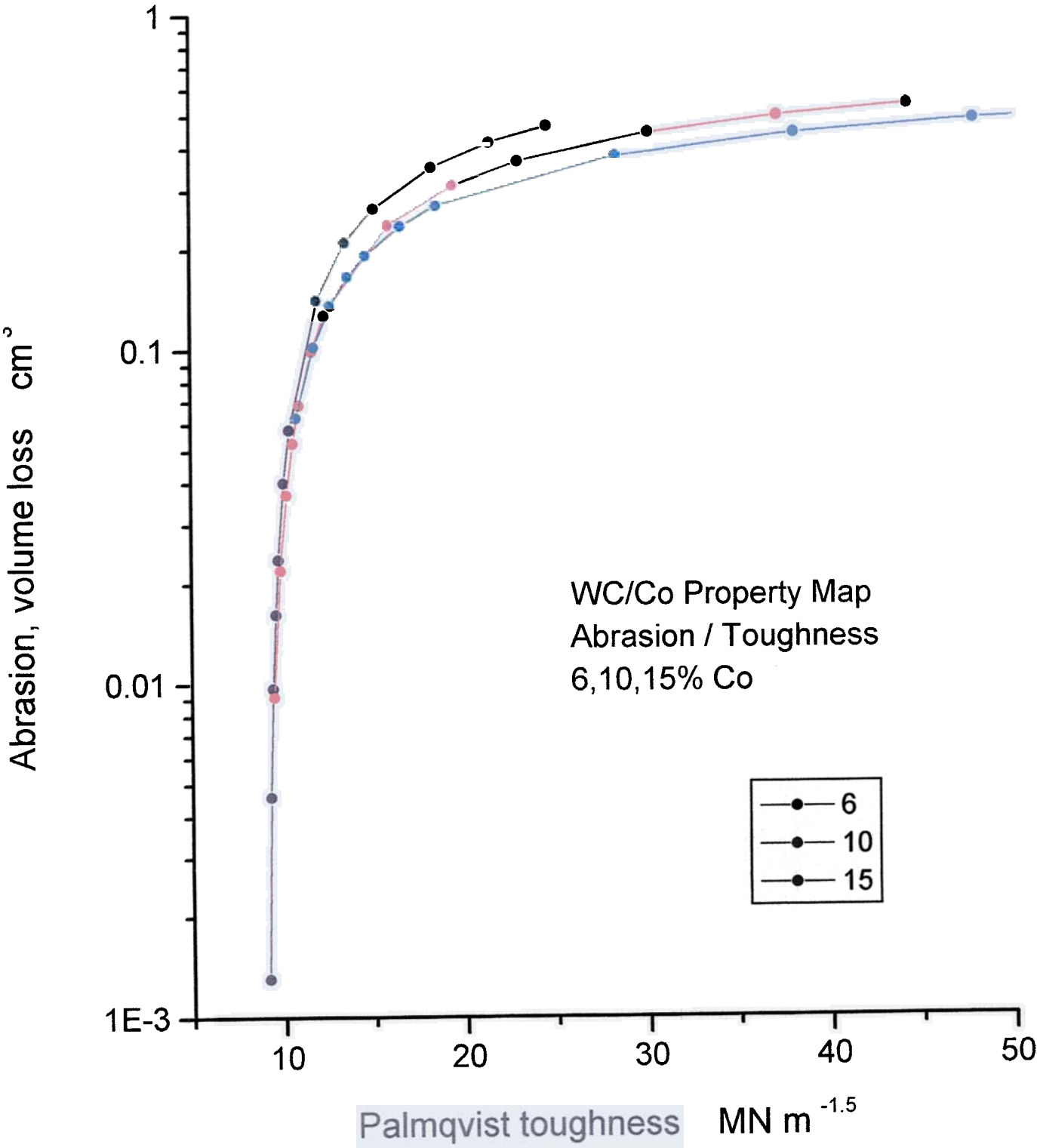


Fig 76 Abrasion (volume loss)/Toughness (Palmqvist) property map

Table 1
Composition

Material	Source	Nominal Binder content wt%	Density†† Mgm ⁻³	Composition†††				
				Co	Ni	Cr	Fe	Mo
MA6	Marshalls	6	14.89	6.28	< 0.1	< 0.1	0.12	< 0.1
MA10	Marshalls	10	14.51	9.86	< 0.1	< 0.1	< 0.1	< 0.1
MA15	Marshalls	15	13.94	15.38	< 0.1	< 0.1	< 0.1	< 0.1
MA20	Marshalls	20	13.54	19.55	< 0.1	< 0.1	< 0.1	< 0.1
MA24	Marshalls	24	13.26	23.37	< 0.1	< 0.1	< 0.1	< 0.1
MAN6	Marshalls	6*	14.95	0.32	5.43	< 0.1	< 0.1	0.44
MAN10	Marshalls	10*	14.58	0.24	9.83	< 0.1	< 0.1	< 0.1
CW15F	CW Carbides	15	14.03	14.50	< 0.1	< 0.1	< 0.1	< 0.1
CW15C	CW Carbides	15	13.98	14.83	< 0.1	< 0.1	< 0.1	< 0.1
CW20C	CW Carbides	20	13.53	19.68	< 0.1	< 0.1	< 0.1	< 0.1
CW25C	CW Carbides	25	13.11	24.44	< 0.1	< 0.1	< 0.1	< 0.1
CWN8†††	CW Carbides	8*	14.83	0.51	7.38	< 0.1	< 0.1	< 0.1
T	Hydra	10	14.69	9.14	< 0.1	< 0.1	< 0.1	< 0.1
UC9	Hydra	9	14.55	9.64	< 0.1	< 0.1	< 0.1	< 0.1
M15	Hydra	15	14.01	15.24	< 0.1	< 0.1	< 0.1	< 0.1
T6	Boart Longyear	6	14.90	6.44	< 0.01	< 0.05	0.05	< 0.05
G10	Boart Longyear	10	14.48	9.90	< 0.01	< 0.05	0.08	< 0.05
G15	Boart Longyear	15	14.02	14.86	< 0.01	< 0.05	0.10	< 0.05
N6	Neepsend	6	14.95	6.17	< 0.01	< 0.05	0.01	< 0.05
N10	Neepsend	10	14.46	10.07	< 0.01	0.43	0.02	< 0.05
N15	Neepsend	15	14.10	15.34	< 0.01	< 0.05	0.03	< 0.05
TC6	Teco	6	14.87	6.29	< 0.01	0.27	0.08	< 0.05
T16D	Teco	16	14.02	15.81	< 0.01	< 0.05	0.14	< 0.05
T20D	Teco	20	13.50	21.08	< 0.01	< 0.05	0.09	< 0.05
T25D	Teco	25	13.16	25.48	< 0.01	< 0.05	0.13	< 0.05

Material	Source	Nominal Binder content wt%	Density†† Mgm ⁻³	Composition†††				
				Co	Ni	Cr	Fe	Mo
SHM5CN	Sandvik HM	5**	15.04	3.35	1.10	0.51	0.05	0.09
SHMUF	Sandvik HM	6	15.02	5.96	< 0.01	0.3	0.05	< 0.05
D10	Dymet	10	14.56	9.94	< 0.01	< 0.05	0.01	< 0.05
D15	Dymet	15	14.10	14.74	< 0.01	< 0.05	0.04	< 0.05
DN6	Dymet	6*	14.78	0.35	5.51	< 0.05	0.07	< 0.05
DN10	Dymet	10*	14.58	0.13	9.59	< 0.05	0.07	< 0.05
TC222	Kennametal	6	14.74	6.09	< 0.01	< 0.05	0.48	0.05
K3560	Kennametal	10	14.52	9.69	< 0.01	< 0.05	0.16	0.10
TiC/Mo ₂ C/Ni	Plansee	8*	5.6	Not analysed				

†* Binder content is nominally Co except for * Ni and ** Co/Ni (3/1)

†† NPL measurements

+++ Also contained 0.33 wt% Ta

Table 2
Magnetic Measurements

Material	Nominal Binder content wt%	Coercivity ^{††} , kAm ⁻¹		Magnetic Moment ^{†††}	
		A	B	A μTm ³ kg ⁻¹	B %CoM
MA6	6	7.9		0.89	
MA10	10	7.1		1.50	
MA15	15	7.0		2.34	
MA20	20	6.5		2.89	
MA24	24	6.0		3.31	
MAN6	6*	0.0		0.00	
MAN10	10*	0.0		0.02	
CW15F	15	8.4		2.04	
CW15C	15	5.3		2.15	
CW20C	20	4.1		2.87	
CW25C	25	4.4		3.52	
CWN8	8*	0.0		0.02	
T	10	6.8		1.16	
UC9	9	4.0		1.37	
M15	15	5.1		2.11	
T6	6	11.1	11.2	0.93	6.2
G10	10	6.4	6.7	1.48	9.5
G15	15	5.6	5.7	2.20	14.6
N6	6	14.9	15.0	0.85	5.6
N10	10	17.9	20.9	1.18	7.8
N15	15	13.9	14.9	1.82	12.1
TC6	6	14.4	14.3	0.86	5.5
T16D	16	8.2	8.3	2.10	14.1
T20D	20	6.6	6.7	2.92	19.1
T25D	25	5.8	6.0	3.46	23.0

Material	Nominal Binder content wt%	Coercivity††, kAm ⁻¹		Magnetic Moment†††	
		A	B	A μTm ³ kg ⁻¹	B %CoM
SHM5CN	5*	24.6	39.5	0.36	2.4
SHMUF	6	38.8	25.1	0.70	4.6
D10	10	9.6	9.7	1.41	9.4
D15	15	9.2	9.5	1.86	12.4
DN6	6*	3.3	0.0	0.03	0.0
DN10	10*	1.5	2.6	0.18	1.5
TC222	6	2.5	2.4	0.98	6.4
K3560	10	4.6	4.5	1.37	9.1

† Binder content is nominally Co except for * Ni and ** Co/Ni (3/1)

†† A - Marshalls
B - Sandvik HM

††† A - NPL
B - Sandvik HM

Table 3
Approximate Carbon Contents

Material	Carbon content*	Comment
MA6	H/M	
MA10	H	
MA15	H	
MA20	H	
MA24	H/M	
MAN6	L	
MAN10	L	
CW15F	H/M	
CW15C	H	
CW20C	H/M	
CW25C	H/M	
T	L	
UC9	H/M	
M15	M	
T6	H	Contained some Fe
G10	H	Contained some Fe
G15	H	Contained some Fe
N6	M	
N10	L	Cr
N15	L	
TC6	H/M	
T16D	M	Adjusted for Cr
T20D	M	
T25D	M	
SHM5CN	M	Contained eta-phase

Material	Carbon content*	Comment
MA6	H/M	
SHMUF	L	
D10	H/M	
D15	M/L	
DN6	L	
DN10	M/L	
TC222	H	Contained Fe and Mo
K3560	M	

* H - high, M - medium, L - low.

Based on magnetic moment measurements

Table 4
Grain Size Measurements

Material	Arithmetic mean linear intercept (amli) μm	Number of intercepts	$1/\text{amli}$ μm^{-1}	$1/\text{sqrt (amli)}$ $\mu\text{m}^{-1/2}$
MA6	1.56	260	0.64	0.80
MA10	1.83	303	0.55	0.74
MA15	1.09	270	0.91	0.96
MA20	1.22	267	0.82	0.90
MA24	1.14	202	0.88	0.94
MAN6	0.64	236	1.57	1.25
MAN10	0.80	300	1.26	1.12
CW15F	1.03	201	0.97	0.98
CW15C	1.94	261	0.52	0.72
CW20C	2.17	256	0.46	0.68
CW25C	2.14	210	0.47	0.68
CWN8	0.83	224	1.20	1.10
T	2.03	285	0.49	0.70
UC9	4.90	202	0.20	0.45
M15	2.04	238	0.49	0.70
T6	1.24	299	0.80	0.90
G10	1.76	312	0.57	0.75
G15	1.93	271	0.52	0.72
N6	0.78	229	1.29	1.13
N10	0.40	289	2.51	1.58
N15	0.56	278	1.79	1.34

Material	Arithmetic mean linear intercept (amli) μm	Number of intercepts	1/amli μm^{-1}	1/sqrt (amli) $\mu\text{m}^{-1/2}$
TC6	0.86	275	1.16	1.08
T16D	0.94	308	1.07	1.03
T20D	1.02	274	0.98	0.99
T25D	1.11	244	0.90	0.95
SHM5CN	0.35	207	2.86	1.69
SHMUF	0.15	223	6.78	2.60
D10	1.14	207	0.88	0.94
D15	0.88	220	1.13	1.06
DN6	0.67	244	1.49	1.22
DN10	0.84	198	1.19	1.09
TC222	3.59	182	0.28	0.53
K3560	2.75	203	0.36	0.60

Table 5
Abrasion Test Results

Material	HV30 NPL	Density Mg m ⁻³	Abrasion Vol loss, cm ³ Al ₂ O ₃	Abrasion Vol loss, cm ³ SiO ₂
MA6	1265	14.89	0.112	
MA10	1230	14.51	0.182	
MA15	1080	13.94	0.313	
MA20	991	13.54	0.439	
MA24	860	13.26	0.504	
MAN6	1535	14.95	0.054	
MAN10	1280	14.58	0.160	
CW15F	1192	14.03	0.235	0.028
CW15C	1043	13.98	0.308	0.048
CW20C	890	13.53	0.445	0.068
CW25C	804	13.11	0.528	0.097
CWN8	1391	14.83	0.088	0.015
T	1218	14.69	0.164	
UC9	982	14.55	0.292	
M15	1028	14.01	0.330	
T6	1494	14.90	0.068	0.0067
G10	1238	14.48	0.190	0.027
G15	1100	14.02	0.300	0.048
N6	1565	14.95	0.034	
N10	1630	14.46	0.034	
N15	1255	14.10	0.14	
TC6	1589	14.87	0.036	0.0054
T16D	1227	14.02	0.253	0.028
T20D	976	13.50	0.393	0.067
T25D	879	13.16	0.532	0.098

Material	HV30 NPL	Density Mg m ⁻³	Abrasion Vol loss, cm ³ Al ₂ O ₃	Abrasion Vol loss, cm ³ SiO ₂
SHM5CN	1971	15.04	0.0072	0.0009
SHMUF	2146	15.02	0.0024	0.0002
D10	1311	14.56	0.111	0.016
D15	1204	14.10	0.193	0.017
DN6	1591	14.78	0.047	0.0096
DN10	1311	14.58	0.122	0.019
TC222	1156	14.74	0.222	0.029
K3560	1156	14.52	0.239	0.032
TiC/Mo ₂ C/Ni*	1470 ⁺	5.83	0.400	-

*Handbook value (K Brookes - World Directory)

Table 6
Hardness and Palmqvist Toughness Tests

Material	HV30 NPL	Rockwell HRA60	Palmqvist crack length μm HV30/60	Palmqvist crack length μm HV100	Palmqvist toughness Wg HV30 N mm^{-1}	Palmqvist toughness Wg HV100 N mm^{-1}	Palmqvist toughness Wk HV30 $\text{MN m}^{-3/2}$	Palmqvist toughness Wk HV100 $\text{MN m}^{-3/2}$	HV100 NPL
MA6	1265		195		1509		12.1		HV100
MA10	1230		252		2336		14.7		
MA15	1080		151		3898		18.1		
MA20	991			104		9433		26.3	950
MA24	860			64		15328		31.8	860
MAN6	1535		410		718		9.2		
MAN10	1280		173		1701		12.9		
CW15F	1192	87.6		341		2877		15.7	1119
CW15C	1043	85.8		72		13625		32.2	992
CW20C	890	83.9		52		18865		35.7	878
CW25C	804	82.3		33		29727		42.7	799
CWN8	1391	89.6	182		1617		13.2		

Material	HV30 NPL	Rockwell HRA60	Palmqvist crack length μm HV30/60	Palmqvist crack length μm HV100	Palmqvist toughness Wg HV30 N mm^{-1}	Palmqvist toughness Wg HV100 N mm^{-1}	Palmqvist toughness Wk HV30 $\text{MN m}^{-3/2}$	Palmqvist toughness Wk HV100 $\text{MN m}^{-3/2}$	HV100 NPL
T	1218								
UC9	982								
M15	1028								
T6	1494	90.7	347	1012	848	969	9.9	10.3	1436
G10	1238	87.9	107	348	2750	2819	16.2	15.9	1162
G15	1100	86.3		179		5480		21.0	1047
N6	1565		392		751		9.5		
N10	1630		361		815		10.1		
N15	1255		198		1486		12.0		
TC6	1589	91.2	324	974	908	1007	10.5	10.9	1540
T16D	1227	87.3		268		3660		17.8	1126
T20D	976	85.5		74		13257		31.4	965
T25D	879	83.9		72		13625		29.8	847
SHM5CN	1971	93.5	530		555		9.2		
SHMUF	2146	94.4	709		415		8.3		

Material	HV30 NPL	Rockwell HRA60	Palmqvist crack length μm HV30/60	Palmqvist crack length μm HV100	Palmqvist toughness Wg HV30 N mm^{-1}	Palmqvist toughness Wg HV100 N mm^{-1}	Palmqvist toughness Wk HV30 $\text{MN m}^{-3/2}$	Palmqvist toughness Wk HV100 $\text{MN m}^{-3/2}$	HV100 NPL
									HV100
D10	1311	89.2	104	412	2381	2381	16.9	15.3	1279
D15	1204	88.3		266	3688	3688		18.1	1155
DN6	1591	91.5	338				10.3		
DN10	1311	89	87	413	2375	2375	18.5	15.0	1231
TC222	1156	86.5		377	2602	2602		14.5	1056
K3560	1156	86.9		221	4439	4439		18.9	1046