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Hardmetals – Microstructural Design, Testing and Property Maps

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Summary

The production of WC/Co hardmetals and their analogues is often considered to be a mature technology. In recent years however there has been a considerable amount of stimulating research where the concepts of microstructural design have been used to produce alternatives to the conventional two-phase structure. The potential of microstructural design is reviewed, particularly the possibilities of performance improvement via changes in size, shape and distribution of the phases. For example, ultrafine grained materials are key technology drivers and pose severe measurement challenges.

Hardmetal technology is also well served by established and standardised laboratory bench-marking property tests such as hardness, magnetic properties, density etc. Recently there has been extensive activity in a number of performance-related testing areas such as wear, fracture and fatigue. These are also reviewed, bearing in mind their ability to discriminate between the effects of differences in microstructural design.

Finally, the concept of property mapping is introduced as a tool for providing a framework for optimising properties. Their utility in correlating performance properties and their relationships with microstructural parameters is evaluated. Their potential for quantifying the differences in properties that unconventional microstructures might offer is also discussed.

KEY WORDS: Microstructure, Design, Property Maps, Fatigue, Wear.

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1 Introduction

Hardmetals, cermets and other sintered hard materials are used in a very diverse range of applications. The use of hardmetals is a mature technology. Industry is currently well served by a range of baseline established standards [1] which, if properly followed with good attention to correct quality procedures, will ensure consistent products. However, even with these standards it is essential to have a full understanding of the effects of test method variables. For example, process dependent grinding stresses introduced during testpiece preparation can change apparent bend strength by up to 100% [2]. Consequently, laboratory benchmark testing is vital, in particular for:

- Characterising structural effects
- Comparing materials
- Quality control
- Quantification of properties

Industry and supporting research organisations now use a wide variety of tests, some of which are standardised and of longstanding pedigree, for example, density measurements. Others, that are thought to be relevant and fairly well understood have some limitations, such as bend testing (transverse rupture tests). Finally, there are research or in-house methods, and it is significant that many of the properties which have a strong influence on the performance of hardmetal products, such as corrosion, fatigue, impact, wear and high temperature strength and toughness, are often measured, but not always by standard test methods.

Key microstructural parameters self-evidently control material properties and thus influence the interpretation of the results of test methods. New hardmetals based on WC/Co are evaluated by industry on a continuous basis, particularly to examine new grades 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. For this purpose two types of property map are discussed: one where the property is plotted against a microstructural feature such as WC grain size or Co binder phase content and one where different properties, such as hardness and toughness are mapped against each other.

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In summary, the paper comprises sections on

- Microstructural Design
- Recent developments in testing
- Property maps

and underlines the importance of baseline understanding for the interpretation of new materials.

2 Microstructural Design

WC/Co hardmetals are generally manufactured to comprise two phases, WC and Co, where Co is an alloy of Co-W-C and WC is stoichiometric. WC/Co is a pseudo-binary section in a three component system (W, C and Co). If the processing conditions are such that the carbon content is either too high or too low then other phases are present in the structure, i.e. graphite when the C content is high and eta-phase (a mixed Co, W carbide) when the C content is low. The structure of two phase WC/Co hardmetals is conventionally defined by these key parameters:

- Grain size of the WC phase
- Co binder mean free path
- Volume (or wt) fraction and composition of the Co binder-phase

There are no standards for the definition of feature size in hardmetal structures. In their absence the number average linear intercept is used both for the WC grain size and the Co binder-phase mean free path, as measured on 2-D polished and etched sections.

The current most important driver in microstructural design is the reduction in WC grain size. Powders in the nanometre size range are available. The technological challenge is to maintain this small crystal size in the sintered product. Property maps (see section 4) indicate that there are substantial gains to be made in abrasion resistance and hardness from a reduction in the grain size. It is imperative to develop suitable methods of characterisation in order to validate the model predictions. However, there is considerable difficulty in measuring the grain size when the crystals are sub 0.1 μm. Co mean free path and distribution play a crucial role in providing adequate toughness in conventional WC/Co hardmetals and some consideration should be given to this parameter when developing ultrafine grained structures.

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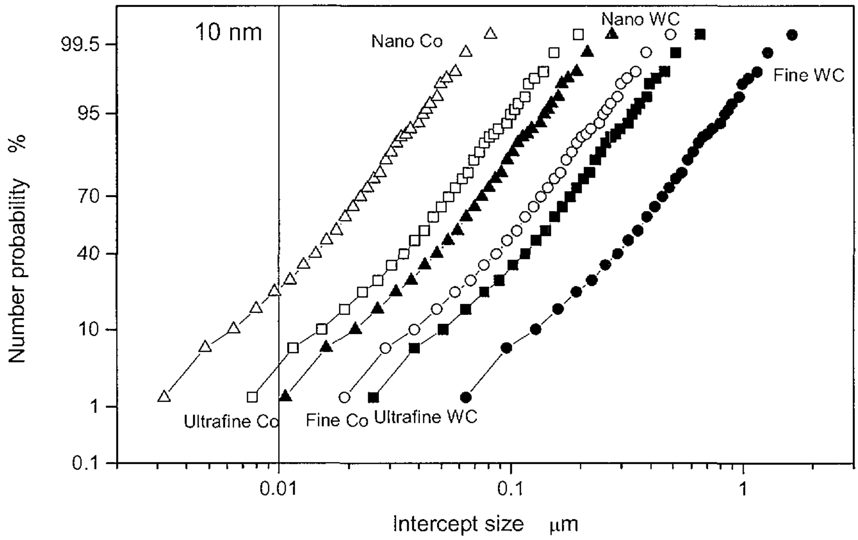

Fig 1 Co and WC measured and calculated intercept distributions in ultrafine grained structures.

In conventional hardmetals the Co intercept (mean free path) distribution is linked to the WC intercept distribution [3]. This is shown in Fig 1 where a plot is given of a measured WC intercept distribution in a 10%Co ultrafine grained hardmetal plotted as number probability against log intercept size compared with a calculated Co intercept distribution. It can be seen that as the mean value of the WC intercept distribution decreases it is not possible to maintain similarity in Co mean free paths since the Co intercept values at the lower end of the distribution are not physically realistic when the calculated size is less than atomic dimensions. Even at the scale of 10 nm the properties of Co are unlikely to be similar to those of larger domains. A change in the morphological relations between the WC and Co can thus be predicted and this will clearly impinge on the properties in ways which have yet to be determined. There are added implications for the use of magnetic techniques, such as coercivity, for the quality control of structure and further work is needed to evaluate binder phase distribution as well as the measurement of WC grain size in these nano and ultrafine grained materials.

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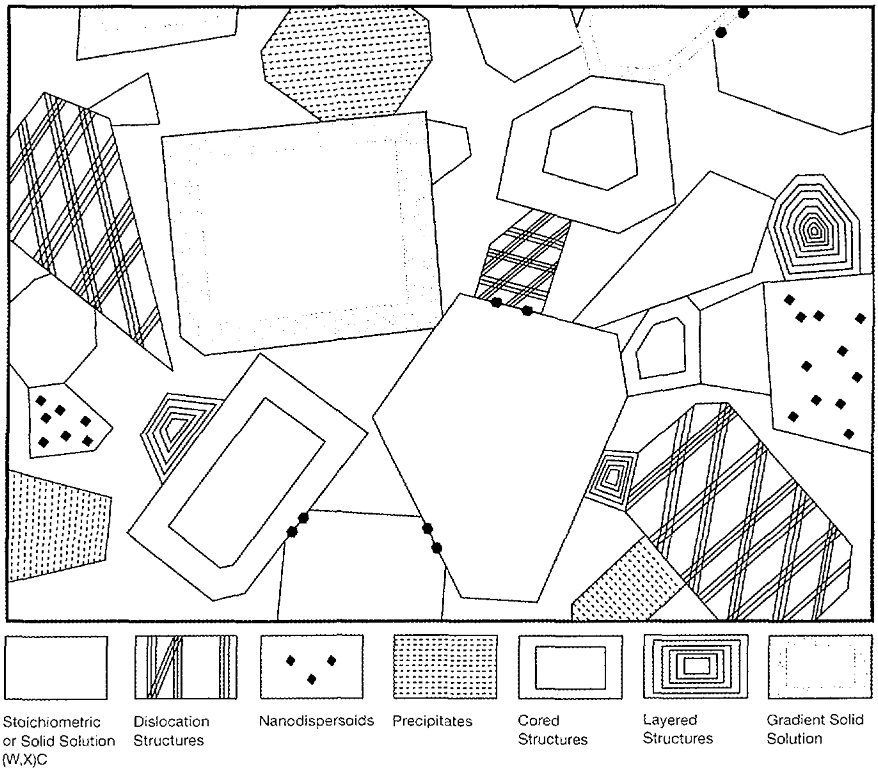

Fig 2 Schematic diagram of intrinsic microstructural parameters.

Many of the key strengthening and toughening methods common to physical metallurgy, such as solid solution strengthening, phase transformations, precipitation hardening, etc, have been used in the development of WC/Co materials. These can be divided into *intrinsic* and *extrinsic* structure-related mechanisms.

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Intrinsic factors relevant to the WC phase [Fig 2] can include:

Solid solution	- e.g. Mo, which can partition between binder and hard phase.
Orientation	- the hardness of individual crystals can vary by a factor of 2, dependent on orientation.
Dislocation structures	- recent high pressure studies [4] indicate that beneficial mechanical properties may accrue from changes in the internal dislocation structure (twins, stacking faults, tangles).
Nanoreinforcement	- the principles adopted by the ceramic community (additions of nano-sized carbides, oxides, nitrides etc) to increase strength. Either at boundaries or intragranular.
Precipitation	- a hardening mechanism not yet evaluated in WC.
Multiphase or layered or core/rim structures within individual crystals	- perhaps taking advantage of epitaxial growth between similar crystal structures (TiB_2/WC etc).

Intrinsic factors applicable to the binder phase could be:

Solid solution	- alloying by W and C well understood. Other elemental additions (Ni, Ru, Fe, Cr, Mo and combinations) are fairly well understood but there is more scope for tailoring properties to performance (corrosion, fatigue, etc).
Precipitation	- Co_3W in low C WC/Co hardmetals; science reasonably well understood.
Phase homogeneity and transformations	- fcc/hcp; difficult to control independently of other parameters. Martensitic structures in Fe-based binders.
Multiphase structures	- Ni alloy gamma/gamma prime (γ/γ') analogues; some science developed but Co-Ni(X) γ/γ' structures less well understood.
Intermetallics	- Aluminides investigated but other types could merit evaluation.

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Clearly there are many possibilities either individually or in combination. Most of these mechanisms predict higher strengths to different degrees [5] but less is known of the potential changes to toughness. At this stage in the evolution of predictive composite microstructural design it is still necessary not only to measure the toughness of structures with altered states but also to be able to compare them with baseline properties. For this purpose materials with single phase WC and a Co(W,C) alloy intermediate between the graphite and eta-phase fields should be used.

Extrinsic mechanisms follow from the principles of composite engineering, either on the level of individual phases or with more macroscopic multi-material morphologies. At the level of the individual phases, e.g. WC and binder, the two most important factors are shape and distribution, although in principle it is difficult to independently change the relevant parameters for each phase as there are space filling constraints on the binder phase.

The unconstrained shape of single crystal WC is a truncated trigonal prism of aspect ratio dependent on the chemistry of the growth conditions. Two dimensional sections observed in conventional micrographs are typical of triangular (basal plane) or prismatic sections through these shapes. It has been shown in both WC/Co and WC/Ni systems that either more platelike crystals [6,7] or more rounded shapes [8] can be developed that result in shifts in the hardness/toughness map either through constraints on the crack morphology in finer grained materials or through changes in the binder-phase size distribution. This would appear to be a fruitful area for further research, as is demonstrated by other papers in this 15th Plansee Seminar [9,10].

With regard to size distribution there are two key aspects:

- changes in feature distribution width (either WC, binder or both) in a monotonic sense
- size mixes of definite modality (bimodal, multimodal, etc) [11,12]; again either for WC and/or binder.

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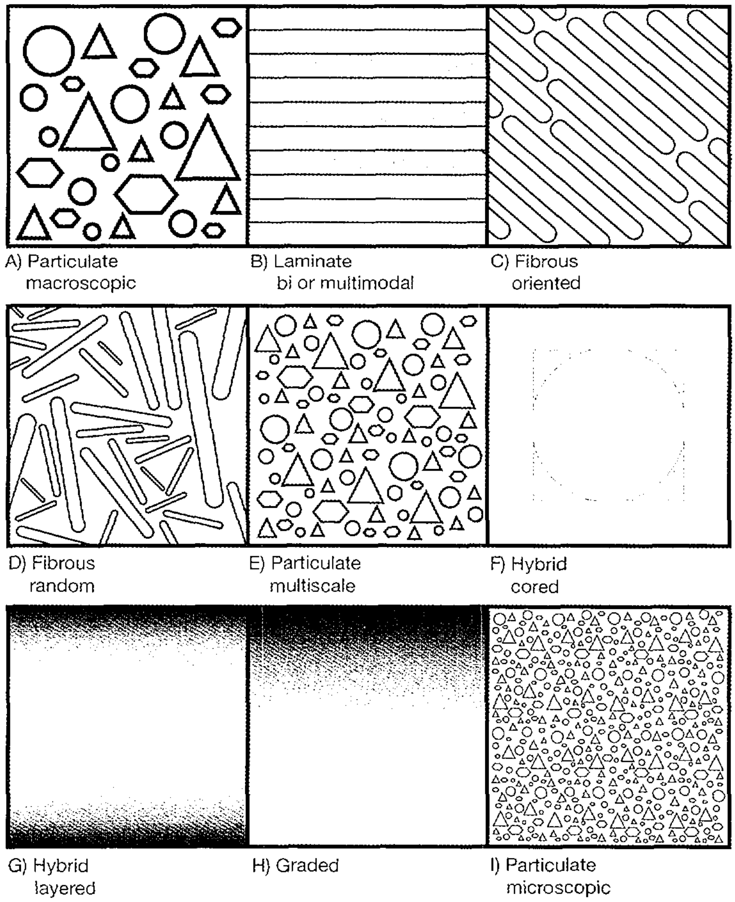

Fig 3 Schematic diagram - composite architectures.

In many cases what appear to be bimodal structures to the eye are difficult to quantify as such using image analysis and the measured distribution can be monomodal, but of wide dispersion. Clearly the issue here is the development of agreed methods of characterising the feature distribution parameters – for both carbide and binder, particularly for the definition of uniformity of size [11,13]. A further aspect of distribution is that of clustering. In principle this can be assessed through measurements of nearest neighbour distances or perhaps

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through the more traditional parameter of contiguity in hardmetals. However, this parameter may not be easy to manipulate independently of changes in other features, but it should not be overlooked as it may play a significant part in controlling strength and fracture [14].

Other types of extrinsic factors affecting microstructural design are multimaterial composite architectures (Fig 3). These can work at many levels, from scales of 5-10 grains up to dimensions of millimetres. The possibilities are many, and are limited only by the imagination and practical feasibility, but could include the classic particulate, fibrous and laminated structures familiar to polymer composite technologies. In this case the matrix/reinforcement couples can be metal/hardmetal; hardmetal/metal or hardmetal/hardmetal. As well as bimaterial types, multimaterial contributions are theoretically possible. Good examples of the particulate type are the Fang et al [15] metal/ hardmetal and Newcomer [16] hardmetal/hardmetal structures. Since one can use powder metallurgical techniques to vary the microstructural features on both a microscopic and macroscopic scale over extremely wide ranges the scope for new research is very considerable. These principles have been used recently by Berns et al to develop ferrous-based multi-materials [17] with enhanced hardness/toughness characteristics. The driving force as always is to move the hardness/toughness combination away from the relations that define conventional materials, either by increasing toughness at equivalent hardness or increasing hardness at equivalent toughness [18]. Hybrid and graded materials fall also within this class and here measurement techniques are needed for assessing the spatial variation in mechanical behaviour as well as interpreting the overall response of the structure. In these materials the global mechanical response will be greatly influenced by the anisotropy of local properties, from the level of the WC crystals upwards in scale. Understanding this anisotropy in behaviour and its scale dependence is therefore a fundamental requirement in the development of materials with macroscopic composite architectures.

3 Developments in Testing

The technologies for testing hardmetals continuously evolve. Two test techniques are selectively reviewed to illustrate the development of test methods, the interpretation of test results and their relevance to property maps.

- S-N Fatigue
- Abrasive Wear

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This choice follows the necessity to develop test methods that are cost effective and have wide applicability in the selection of suitable materials. Abrasive wear is discussed because a single expression can be derived relating abrasion to hardness that is useful in property mapping. By way of contrast S-N fatigue is discussed because it provides an example of mechanical behaviour that is less straightforward in this respect.

3.1 Fatigue tests

Many different kinds of tests method have been used to investigate the fatigue behaviour of hardmetals including fatigue crack growth, compression, tensile, S-N and contact fatigue modes. However, the most developed method in recent years has been that applied by the Erlangen group [19] using an S-N approach to establish a fatigue life for different hardmetals. However, their apparatus is rather specialised and not obviously amenable to wider use. Consequently at NPL we have investigated the use of V-notched testpieces to obtain S-N data through $R > 0$ bend tests using a straightforward, more commonly available, bend jig.

Rectangular testpieces are diamond ground and then V-notched [2] at the centre of one of the faces to a nominal depth of 1 mm using a 0.5 mm radiused diamond resin-bonded wheel. The notched testpieces are annealed at 800 °C for 1 h in a vacuum to relax residual stresses. Notched S-N fatigue bend tests are performed in a test jig with a span of 30 mm.

Typical results for two hardmetals are shown in Fig 4 and they confirm correspondence with results from the Erlangen group underpinning the typical S-N type behaviour of hardmetals and the ability to discriminate. However, a key issue is how many tests need to be performed to ascribe a given level of confidence for lifetime prediction. The results of a study using randomly selected data sets of size N_R from the total population N_T is shown in Fig 5 where it can be seen that a minimum of about 20 tests is needed to confer an uncertainty of about 15% on the slope of the fitted parameters to a linear correlation between maximum stress and cycles to failure N_f. Consequently the derivation of unique constitutive expressions describing S-N behaviour that will effectively discriminate between different materials will not be straight-forward because of the inherently larger scatter in data in fatigue.

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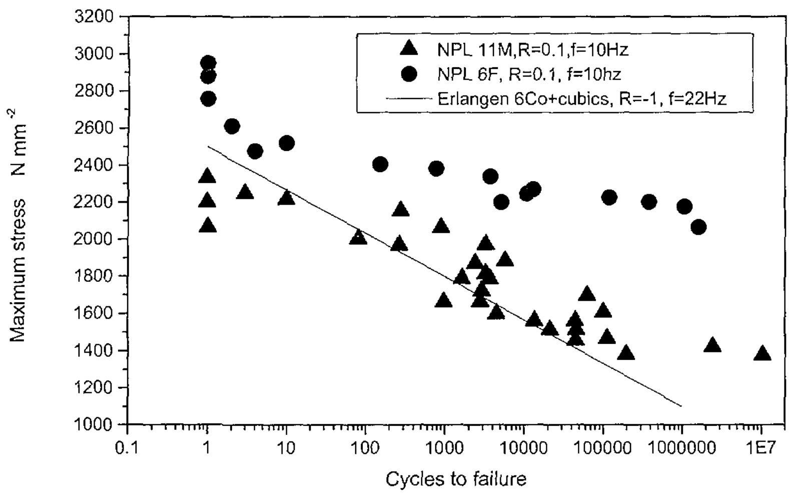

Fig 4 Typical notched bend fatigue test results.

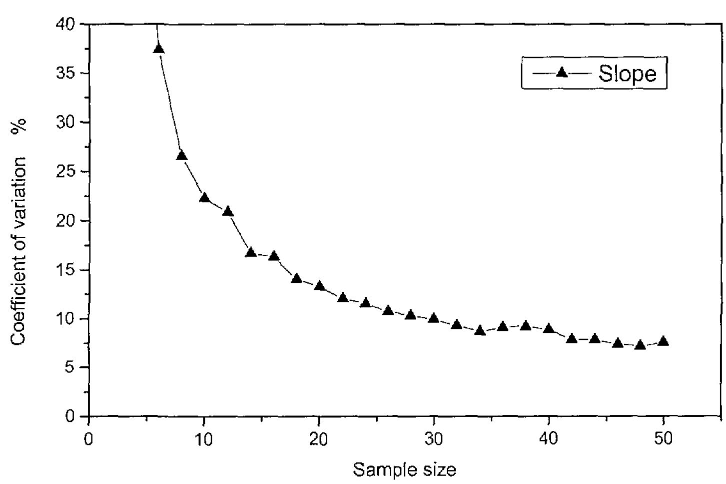

Fig 5 Uncertainties in the S-N slope relation parameter.

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3.2.2 Wear

Assessment of wear resistance is a very important issue from the point of view of end use. However, different wear mechanisms may be appropriate, of which abrasion and erosion are the two most relevant.

The literature on wear behaviour generally fall into two schools

- where there is believed to be a monotonic dependence on hardness [20,21]
- or where the wear behaviour is thought to be dominated by mechanism changes, influenced either by random events in binder and carbide at low values of hardness and bulk deformation mechanisms at higher hardness [22,23].

Other mechanisms caused by oxidative or chemical effects, can also influence the interpretation of test results. Abrasion and erosion test methods are being evaluated at NPL both for their repeatability and reproducibility in order to quantify uncertainty. Quantifying uncertainties gives added confidence in the ability to discriminate materials. Also quantitative relationships are needed between wear parameters and microstructures to underpin the use of property maps. Some of these issues are illustrated with Fig 6 which shows results of the ASTM B611 abrasion test at NPL compared with published data by the University of Witwatersrand group [23]. The results allow an expression to be developed that is applicable to typical grades of commercial WC/Co currently available from HV800-HV2200 such that:

$$A = a \exp[-bH] \qquad (1)$$

where A is abrasion resistance in vol loss (cm^3), H is hardness (HV30) and a and b are constants. It was found that the repeatability of measurement was less than size of the symbols on the graph. The agreement between the NPL and the University of Witwatersrand group [23] indicates that the reproducibility of the test is also excellent. This single expression is clearly useful in underpinning the development of property maps.

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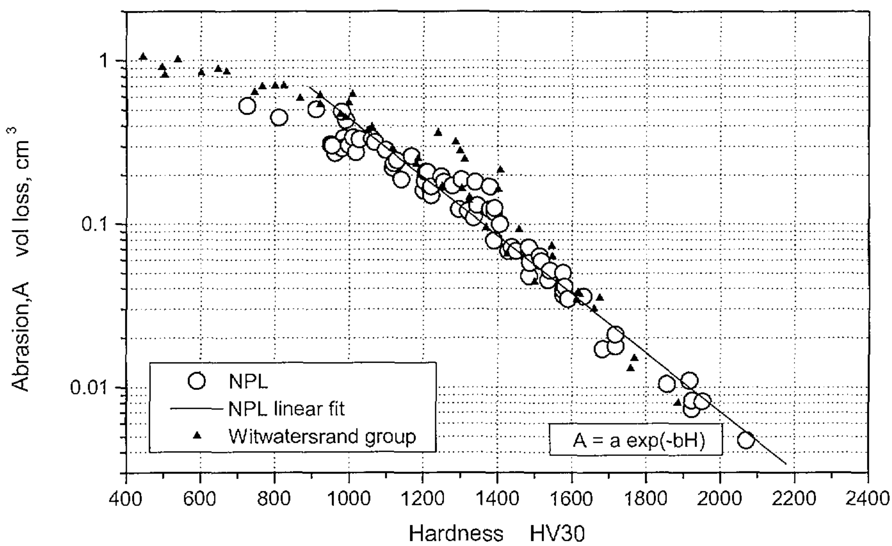

Fig 6 ASTM B611 Abrasion results

4 Property Maps

A structural characterisation exercise was conducted on a set of WC/Co hardmetals with a range of grain sizes and Co contents from 6-25 wt% [24]. The measurements of structure were then analysed for comparison with model predictions from an NDE measurement of magnetic coercivity. As well as coercivity the property characterisation exercise consisted of a measurement of hardness, toughness (by the Palmqvist method) and abrasion resistance. The measurements were used to construct the "property maps". In principle, these maps allow the effects of differences in structure and properties to be more easily compared and can provide a benchmark for the evaluation of new materials.

Two types of property map were considered:

- Structural dependence
- Property comparisons

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In the first type the property of interest is plotted against a microstructural feature that controls that property. Two microstructural features are discussed, 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, the cobalt mean free path or the size distribution of WC grains. However, for this paper the concept of "property maps" is developed assuming a composition approximately in the centre of the two-phase WC/Co region and that there is a conventional WC grain size distribution with the arithmetic mean number intercept, d, as the parameter characterising WC grain size.

Four properties were evaluated to compare with microstructure:

Coercivity, K	Abrasion Resistance, A
Hardness, H	Palmqvist Toughness, T

from which eight property maps based on microstructure can be constructed; K *vs* d, K *vs* W, H *vs* d, H *vs* W, A *vs* d, A *vs* W, T *vs* d and T *vs* W.

Data from measurements on the baseline WC/Co materials [24] were used 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:

T *vs* H   A *vs* H   A *vs* T

4.1 Microstructure property maps

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

$$K = a + b\,(1/d) \tag{2}$$

where a and b are constants, K is the coercivity in kA m^{-1} and d is the WC arithmetic mean linear intercept size in μm. Initial work 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}. This expression did not include a parameter for the variation of Co content and this is needed for comprehensive property mapping of typical hardmetals. Additional work [24] allowed expression (2) to be modified

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to give the variation of coercivity, K, with grain size, d for 6 < Co < 25wt% as follows:

$$K = (c_1 + d_1 * wt\% \; Co) + (c_2 + d_2 * wt\% \; Co) * (1/d) \qquad (3)$$

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 (3) can be plotted as a property map, Fig 7, bearing in mind the constraint that it has not been extensively validated for high values of coercivity equivalent to WC grain sizes (arithmetic linear intercept) less than about 0.5 μm. Additional work is needed to evaluate finer grained materials. A property map using Co wt% content as the variable can also be plotted from expression (3). This is also shown in Fig 7 for values of linear intercept WC grain size of 5, 2, 1, 0.75 and 0.5 μm, respectively.

It is also necessary to be aware that coercivity also varies with carbon content and W content of the binder-phase. It has been assumed that the compositions are approximately in the centre of the two phase field. Further work would be needed to refine expression (3) to allow for this effect. 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 [25].

It is clear from inspecting the property maps in Fig 7 that the coercivity measurements are fairly insensitive to changes in intercept size as the mean value increases beyond about 3 μm.

Hardness can be related to the inverse square root of the intercept size using the Hall-Petch expression [25].

$$H = e + fd^{-0.5} \qquad (4)$$

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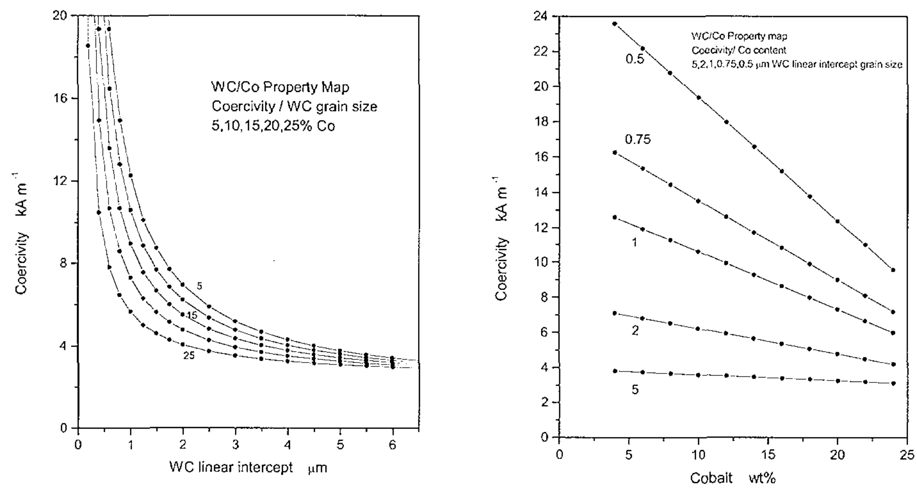

Fig 7 K *vs* d and K *vs* W property maps.

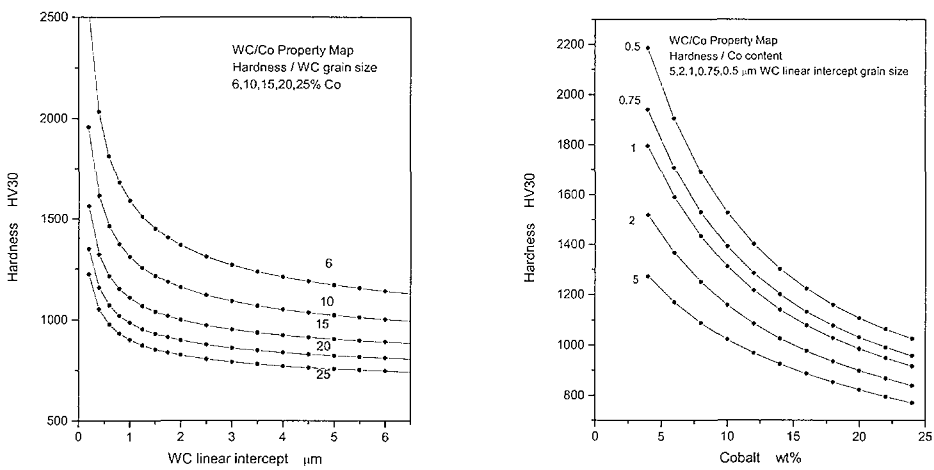

Fig 8 H *vs* d and H *vs* W property maps.

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where e and f are constants, H is the hardness, HV30, and d is the WC arithmetic mean linear intercept size in µm. Further analysis allowed an expression to be written for the variation of hardness, H, with intercept size, d, for 6 < Co < 25 wt% as follows:

$$H = (888 - 9.9 * \text{wt\% Co}) + \frac{(229 + 532 * \exp(-(\text{wt\% Co} - 6)/6.7)}{\sqrt{d}} \quad (5)$$

Expression (5) can be plotted as a property map, Fig 8, bearing in mind it is not validated extensively for ultrafine grained materials. There is some evidence that the Hall-Petch expression is inaccurate for the finer grained materials. Further work is needed to assess materials with WC intercept size less than about 0.3 µm.

A property map using Co wt% content as the variable can also be plotted from expression (5): This is also shown in Fig 8 for different values of the WC linear intercept grain size.

Abrasion resistance, A, is dependent on hardness, H, and it was found [20] that:

$$\log A = g + hH$$

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

however $H = e + fd^{-0.5}$

thus $\log A = i + kd^{-0.5}$ (6)

where i and k are constants, and d is in µm. Analysis of the data on the baseline hardmetals [24] allowed an expression to be written for the variation of abrasion resistance, A, with grain size, d, for 6 < Co < 25 wt% as follows:

$$\log_{10} A = (0.19 - 0.016 * \text{\% Co}) - \frac{(2.075 - 0.133 * \text{\% Co} + 0.0022 * (\text{\%Co})^2)}{\sqrt{d}} \quad (7)$$

Toughness can be related to the Co mean free path [26]. The Co mean free path is linearly related to WC intercept size for materials with conventional WC

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grain size distributions [3]. Therefore the following expression was used to evaluate the Palmqvist toughness results for property mapping:

$$T = m + nd \tag{8}$$

where m and n are constants. Analysis allowed an expression to be written for the variation in Palmqvist toughness with intercept size as a property map:

$$T = 8.8 + (10\^{} (-0.33 + 0.088*\%\ Co))*d \tag{9}$$

This is probably the least well developed expression in this group because of the difficulty of obtaining extensive sets of valid toughness data for WC/Co.

4.2 Comparative property maps

The expressions developed in section 4.1 for the microstructure property maps can be used to derive comparative property maps. Two examples are shown in Fig 9 (T *vs* H) and Fig 10 (A *vs* H). Other combinations are possible, but these are good examples because, industrially, hardness is used quite frequently as the property with which other properties are compared. Also the maps can be plotted for different representative Co contents and for different WC grain sizes.

The first comparative map, Fig 9, shows the relationship between Palmqvist toughness and hardness. The second comparative map, Fig 10, shows the relation between abrasion (vol loss) and hardness. 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 MN $m^{-3/2}$.

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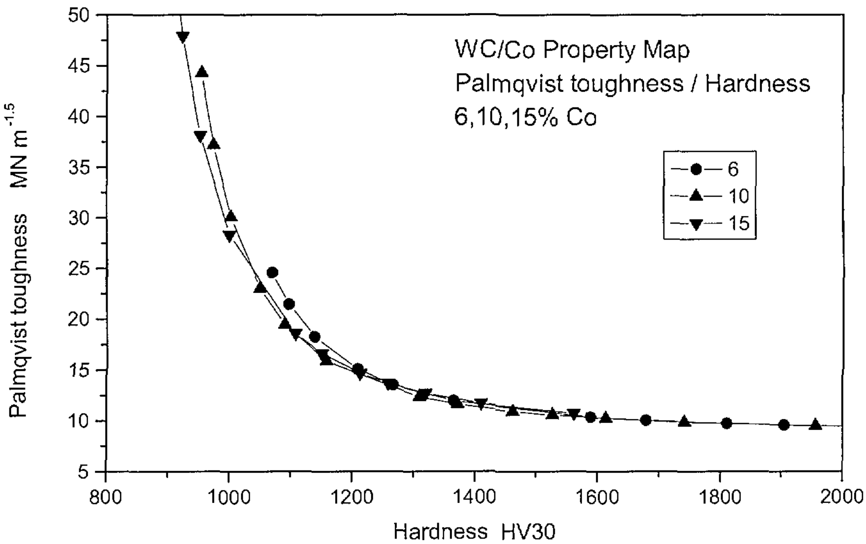
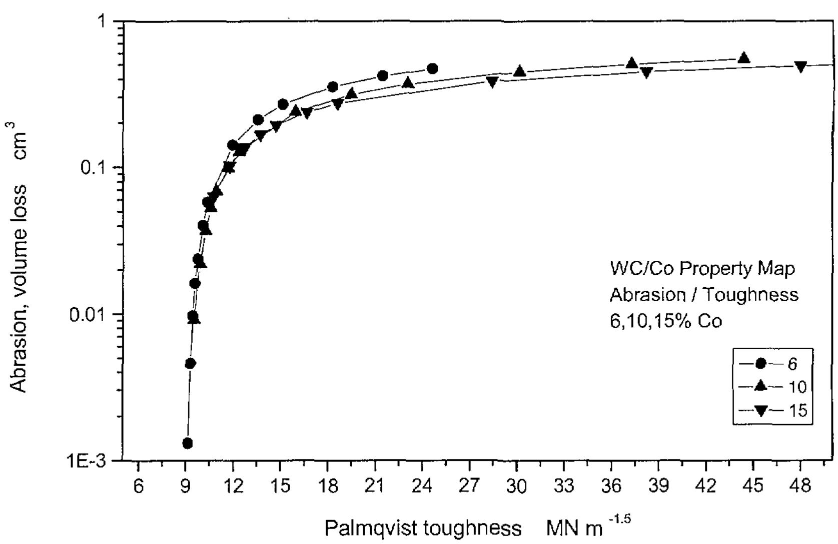


Fig 9 T *vs* H property map.



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5 Summary

There is an increasing trend in the last 10y to investigate unconventional hardmetal structures, for example, with changes in the shape and distribution of the hard and binder phases, with the physical metallurgy of the different phases and with the architecture used to construct the macroscopic appearance, i.e. graded and particulate structures. Thoroughly well characterised property maps for conventional hardmetal structures are vital in order to fully quantify the changes in properties associated with these unconventional structures.

There are an immense number of structural variants to investigate. Thus, there are clear opportunities for the use of microstructural modelling approaches to accelerate the development process. It is vital to understand that many of these innovative structures will be anisotropic in their properties. It is crucial therefore that more understanding is developed of the effects of this anisotropy, both on a macro and a microscopic level. Modelling studies will be especially needed to develop relations between feature distributions, shape and chemistry and to relate predictions from these studies to mechanical property data such as strength, hardness and toughness.

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Transition From HSS Tools to Solid Carbide Tools in the Field of Shaft Tools and the Development of New Types of Carbides

by

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Summary:

The development trends for shaft tools made of solid carbide are presented. The reasons for the rapid acceptance of solid carbide tools in areas formerly reserved for high speed steel tools are explained. The development of tougher types of carbide and more modern coating procedures as well as the use of high speed cutting machines with higher efficiency is examined especially.

Modern carbide types with 10% and 12% cobalt and higher toughness are described. The influence of reducing the average WC grain size is emphasized.

Finally, advanced extrusion processes with screw extrusion presses are explained. They cover a large market segment of the carbide rod production today. The possibilities of finer shaping close to the form of the final product are described.

Keywords:

Extrusion presses, presses for multiple rods, ultrafine grain sizes

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Introduction:

In recent years, there has been a strong increase in the use of shaft tools made of solid carbide worldwide.
This relates to shaft millers and drills with and without internal cooling ducts as well as reamers and tap drills.
While the solid metal tools initially increased strongly in the diameter range from 0.1 mm and 12 mm, an increase in the diameter range from 16 mm to 32 mm can also be observed today.
The increased use of solid carbide shaft tools actually began only 20 years after the boom in turnplates and the related turnplate holders.

There are several reasons to change rapidly to the use of carbide shaft tools

a) Tougher types of carbide have been developed, which nevertheless have the same hardness as before. Through their higher toughness, fields which were previously reserved for HSS have been conquered.

b) Economical coating processes which increase the lifetime and range of possible applications of solid carbide tools have been brought onto the market.

c) Manufacturing machines have been developed, which have the required performance, speed and stiffness necessary for the use of carbide tools. These machines were previously not available in a large selection. These new machines are forcing the replacement of the earlier high speed steel tools in favor of carbide tools.

d) New areas of use have been added for carbide tools, which were not covered adequately by high speed steel tools. For example, machining of fiber-reinforced plastic
Machining of titanium alloys
Machining of stainless steel
Machining of hardened steel

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e) In many cases, cutting work can be performed more quickly and more economically than with high speed steel tools. This leads to a reduction of the investment with the same production quantity. The plants become more flexible through the higher manufacturing speed.
The quality of the products produced also rises because the e-modulus of the solid carbide tools is higher than that of HSS tools.

f) A further important reason for the sharp increase in solid carbide shaft tools is the provision of adequate production capacity.
It is estimated that there was a production capacity of approx. 13,000 to/year for carbide rods in the year 2000. The Kulmbach region in northern Bavaria accounted for 900 to/year alone.
The expansion of the worldwide production capacity is not yet at an end and is increasing, so the use of HSS tools will be on the decline in the foreseeable future.

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2.0 New Developments in the Field of Tough Types of Carbides for Shaft Tools

For years, carbide manufacturers have made efforts to raise the toughness of carbide grades without reducing their high, often desired hardness and resistance to wear.
For many years, there were two main types on the market, namely the K types and the P types, whereby the K types were used mainly for cast iron machining and the P types for steel machining.
Through the development of coating technologies, the main applications of the carbide types shifted more and more into the K area, meaning into types with very low TaC content and no TiC content. With the coated types of carbide, steel was then machined successfully as well.
A so-called 6% was dominant in the K area for a long time, meaning a carbide type with about 6% cobalt content, an average WC grain size of 1.5 µm down to 1.0 µm sometimes.
In addition, they were dosed with VC and TaC in low quantities (approx. 0.2% VC and 1% TaC) to avoid grain growth during the sintering process. Every manufacturer of carbide had this type (see Figure No. 1) in its program in the 70s and 80s.

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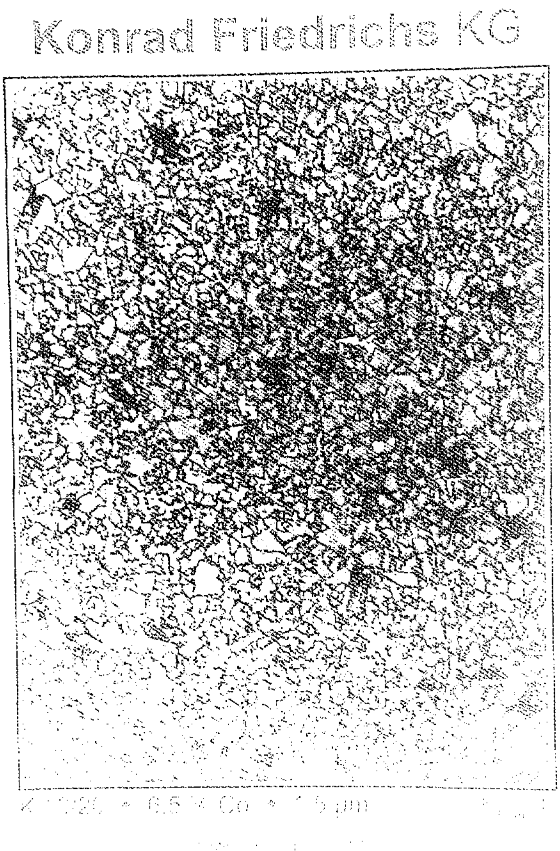

Figure No. 1: grain size structure of a 6 %er

A variation of this was a 6% with a then very fine WC grain of approx. 0.7 µm to raise the hardness and resistance to wear. This type was used primarily in the electronic drill and the reamer area.

The size of the TaC crystals (> 2µm), which led to early cutting break-outs and a reduction of the toughness was extremely annoying with these K types. The so-called RAMET types from an American manufacturer at the end of the 70s and the beginning of the 80s were the first successful types in the K area with Cr_3C_2 in place of TaC.

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At the end of the 80s and the beginning of the 90s, all important carbide manufacturers began to develop a K type for rod manufacturing. It contained 10% cobalt and had an average grain size of 0.65µm to 0.8µm.

CR_3C_2 and some VC were used as doping material. See Figure No. 2.

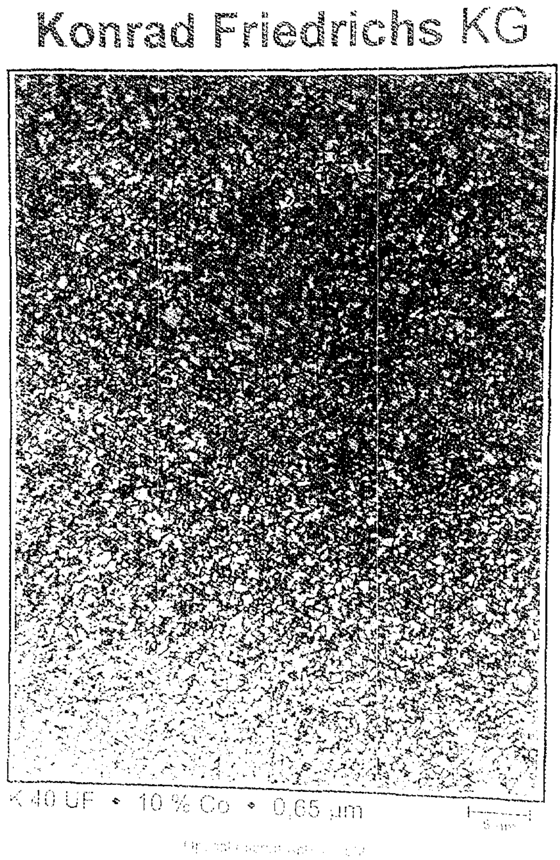

Figure No. 2: grain size structure of a 10 %er

This 10% type has high hardness and resistance to wear and thereby exhibits considerable toughness as well.
This 10% also belongs to the main standard carbide types at almost all important rod manufacturers.

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The meaning of the Cr_3C_2 and VC content was recognized more and more. Variations of the proportion and the quantities of Cr_3C_2 and VC exhibited significant influence on hardness and toughness.

In the mid-90s, 12% came onto the market. The tools of a Japanese manufacturer were distinguished because of their sharply increased resistance to wear and toughness as well (Kobelco).
These carbide types had a significantly higher lifetime in a series of applications with high loading on the tool (diesink milling, machining of hardened steel, machining of stainless steel, milling of titanium alloys, application in aluminum alloys, drilling in fiberglass reinforced plastics).
Figure No. 3 shows the grain structure of the 12% at 1500 times magnification. This 12% distinguishes itself through a further reduction in the grain size of the WC.
It amounts to 0.5µm.
Furthermore, the proportion of Cr_3C_2 and VC was increased again in comparison to the 10%. Further variations were also made in the proportion of the two materials.
This type is gaining more and more in importance and will therefore replace the 10% types increasingly.

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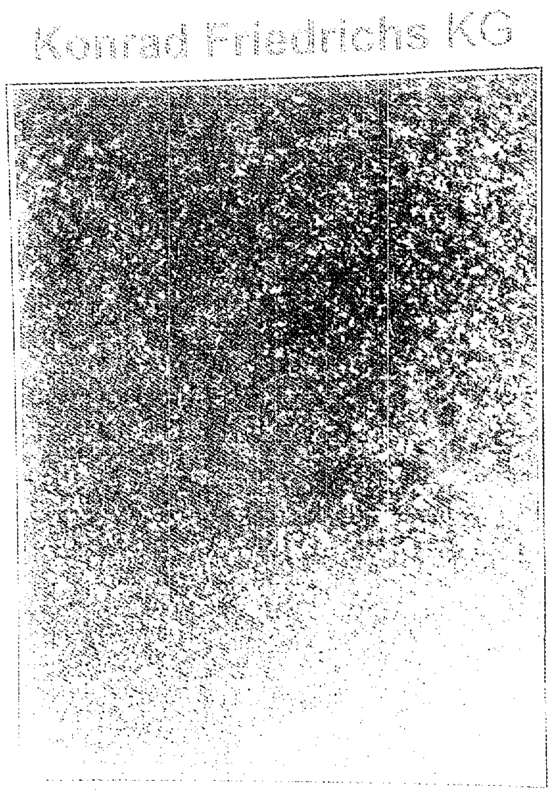

Figure No. 3: grain size structure of a 12 %er with 0.5 micron WC

The grain structures of a 10% and a 12% are to be seen in comparison in Figures No. 4 and No. 5 respectively at 10,000 times magnification.

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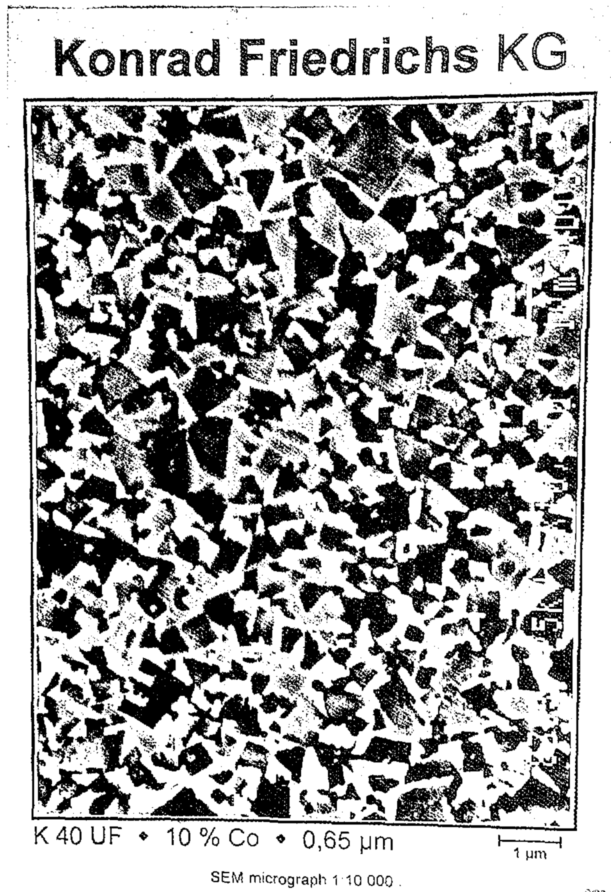

Figure No. 4: 10 %er with magnification 10.000 times

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Figure No. 5: 12 %er with magnification 10.000 times

The transition from an average grain size 0.65µm to an average grain size 0.5µm can be seen clearly.

A further development is therefore the transition to types with an average WC grain size of 0.2µm, which has been taking place recently.

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While the term ultrafine is used for types with 0.5µm grain size, the expression superfine is used to distinguish the 0.2µm types.
In Figure No.6, the grain structure of a superfine carbide can be seen at 10,000 times magnification.

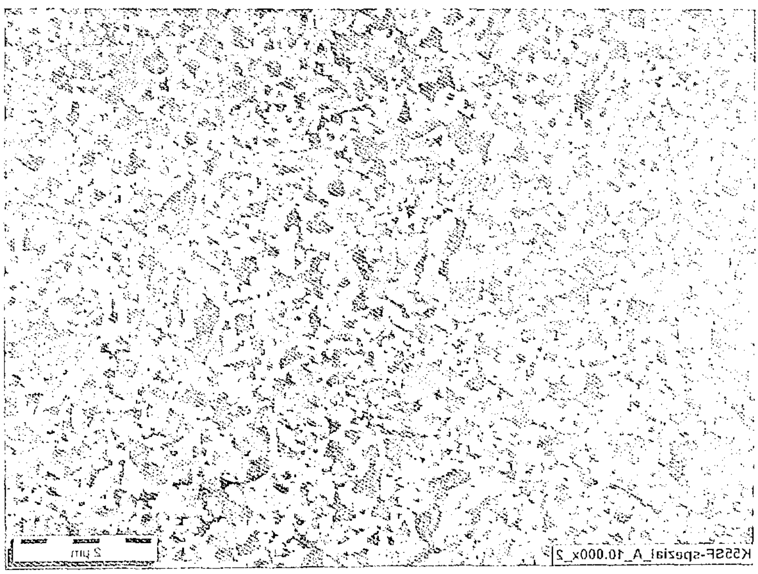

Figure No. 6: superfine carbide grade with magnification 10.000 times

At the present time, these types are used primarily in the field of electronic drills and PC drills.
Hardnesses of 2000 Vickers (93.2 Rockwell) and bending stiffnesses of 4000N/mm^2 are normal here.
The enormous toughnesses of these materials with considerable hardness are to be emphasized.
At the present time, these types of carbide are manufactured with approx. 8% and 9% cobalt. The Cr_3C_2 and VC contents amount to 1.2 % together.
The development of these types will also be followed logically in types with higher Co content (approx. 12%) to achieve further increases in toughness, compared to the old 12% with 0.5µm. The hardness should retain its high level more or less.

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A summarized presentation of the most important K types is given in Figure No. 7, whereby the 12% and the types with 0.2µm average grain size are to be regarded as the latest development of two carbide types for rods at the present time.

Konrad Friedrichs KG

HARTMETALLFABRIK KULMBACH

Typical carbide grade recipies in the K-grades

6 %	6 %	Cobalt	
	1 %	TaNbC	
	0,15 %	VC	
	92,85 %	WC	1,5µm
8 %	8 %	Cobalt	
	1 %	TaNbC	
	0,2 %	VC	
	90,8 %	WC	0,7µm
10 %	10 %	Cobalt	
	0,3 %	Cr_3C_2	
	0,2 %	VC	
	89,5 %	WC	0,65µm
12 %	12 %	Cobalt	
	0,9 %	Cr_3C_2	
	0,4 %	VC	
	86,7 %	WC	0,5µm
9 %	9 %	Cobalt	
	0,63 %	Cr_3C_2	
	0,55 %	VC	
	89,82 %	WC	0,2µm

Figure No. 7: summarize of important k grades

The most important physical and chemical properties of the types described can be seen in Figure 8.

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Type of hard metal	WC %	Co %	TiC/ Ta (Nb) C % or Cr_3C_2 + VC	Density, ISO 3369 [g/cm³]	Hardness HRA, ISO 3738	HV 30, ISO 3878	Magnetic saturation 4π σ [µTm³/kg]	Coercive field strength HC, ISO 3326 [kA/m]	Transverse rupture strength, ISO 3327 [N/mm²]	Porosity, ISO 4505 A	B	C	Grain structure, ISO 4499 α	γ	Classification, ISO 513
KF K 10/20	92,5	6,5	1	14,8	92,0	1660	12	18	2500	≤ 02	00	00	medium/ fine	medium	K 10-K 20
KF K 10 F	92,5	6,5	1	14,8	92,7	1810	12	26	3100	≤ 02	00	00	fine	fine	K 01-K 10
KF K 20 F	90,5	8	1,5	14,6	92,2	1710	15	23	3200	≤ 02	00	00	fine	fine	K 10-K 30
KF K 40 UF	89,5	10	0,5	14,5	91,7	1610	16	21	3600	≤ 02	00	00	fine	-	K 30-K 40
KF K 44 UF	86,7	12	1,3	14,1	92,1	1680	19	26	3800	≤ 02	00	00	fine	-	K 40-K 50
KF K 45 UF	85,7	13	1,3	14,1	91,5	1600	21	24	3900	≤ 02	00	00	fine	-	K 40-K 50
KF K 55 SF special	89,8	9	1,2	14,3	93,2	2000	14	39	4000	≤ 02	00	00	fine	-	-

01/01

Figure No. 8: physical and chemical properties of important k grades

The high bending rupture value and the hardness value at the same time of the carbide type with 0.2µm average grain size of the WC are remarkable. These types of carbide metal are getting closer and closer to HSS because of their toughness, even if the distance is still relatively large.

It is important to note that, in spite of higher hardness, a large bending rupture strength has also been achieved.

A schematic representation of the relationship between hardness and toughness is shown in Figure No. 9.

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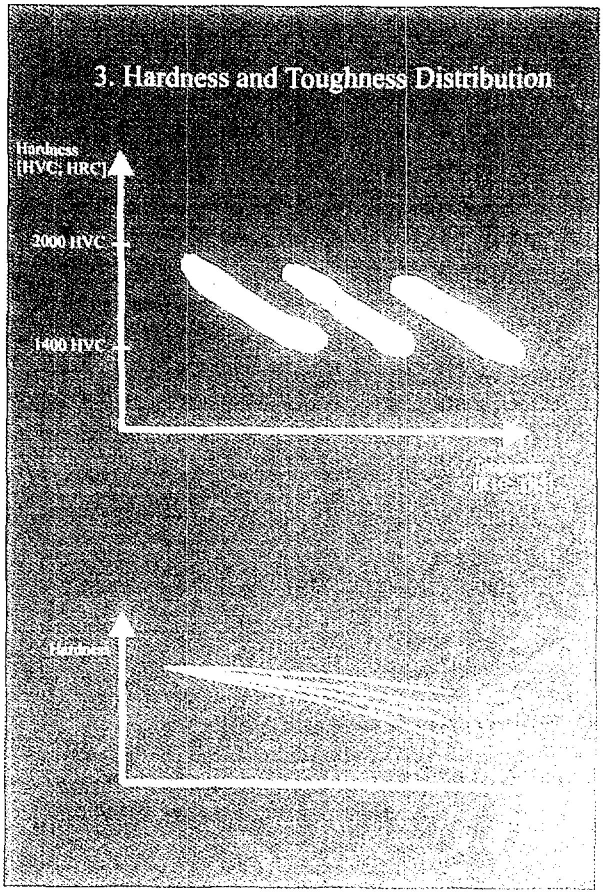

Figure No. 9: relationship between hardness and toughness

Every one of the three carbide types can be varied with respect to its relationship between hardness and
toughness by, for example, changing the proportion of Cr_3C_2 and VC or the total quantity of C43C2 + VC.
This means that sub-types for special applications can easily be manufactured from one type of carbide.
A change in the grain size can also lead to a different carbide with all other parameters fixed as can be seen in Figure No. 9. We will not have a long wait until interesting developments, especially in this field of the variations, are available.

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3.0 Production Methods of Carbide Rods Which Are Used for Cutting Tools

The methods of cutting rectangular rods from cold isostatic pressed blocks and making them into round rods through grinding processes has long been out-of-date. Rods are pressed today, for example, from granulate between upper and lower stamps and matrices horizontally or vertically, whereby the rod lengths are very limited. Lengths which correspond to the standard dimensions of catalog tools are produced, whereby the shrinkage during sintering must be taken into account.

Another, very frequently used procedure today is the pressing of round rods of carbide powder in thick-walled, well-closed polyurethane tubes with water pressure from the outside. The pressure then amounts to approx. 2000 bar.

The most frequently used process is the extrusion process to press out rods of all cross-sections. The length of the rods is almost unlimited thereby and depends only on the type of extruder used. A distinction is made between piston extruders and screw extruders.
Screw extruders can work continuously, given the availability of enough mass to be pressed out and, if necessary, produce rods kilometers long if the required cutting and stacking fixtures are available behind the presses. Piston extruders can work without interruption only as long as there is enough material contained in the cylinder in which the piston works.
The cross-sections of the rods to be pressed depend upon the plastification agent used.
Plastification agents which permit the extrusion of rods with a maximum diameter of 34 mm (sintered diameter) today have been developed by the author.
The problem with all plastification agents is that, although they are very necessary with extrusion pressing, they interfere very much with the sintering process later.

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These plastifiers must be removed before the sintering, at best before the rods reach the sintering oven.

The cheapest and simplest process at the present time is a drying process in simple air drying cabinets, during which the majority of the plastification agent is dried out.

The rest remaining permits rapid, problem-free sintering without the risk of cracking.

Screw extruders have been developed especially for the production of rods with internal cooling ducts. They allow a very exact and precisely-defined pitch of the spiral cooling ducts for drill bits with small diameters and relatively large lengths.

Figures No. 10 and No. 11 show a modern screw press with cutting fixture and transport table as well as line camera and monitor to control and adjust the angle of the pitch, based on a patented process.

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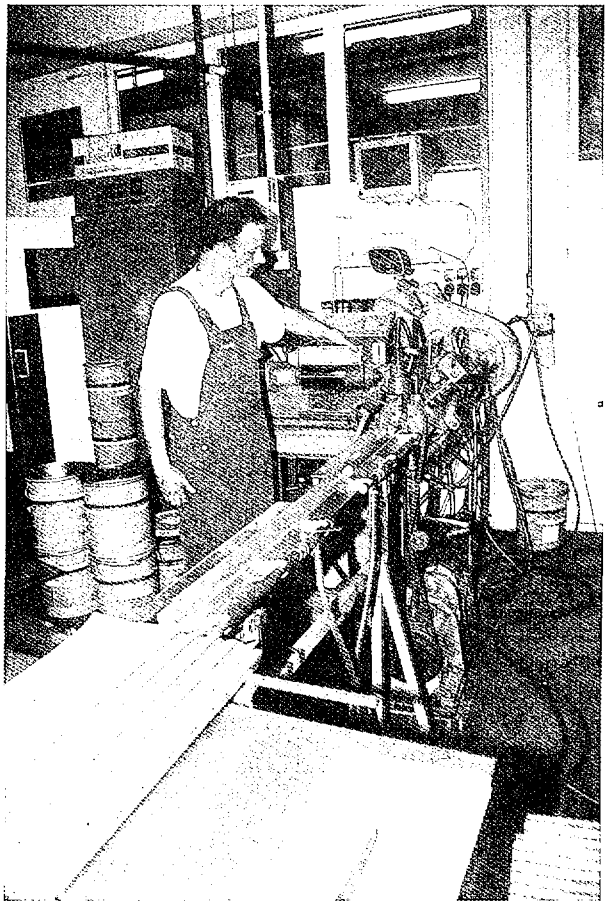

Figure No. 10: Screw extruder for spiral coolant hole rods

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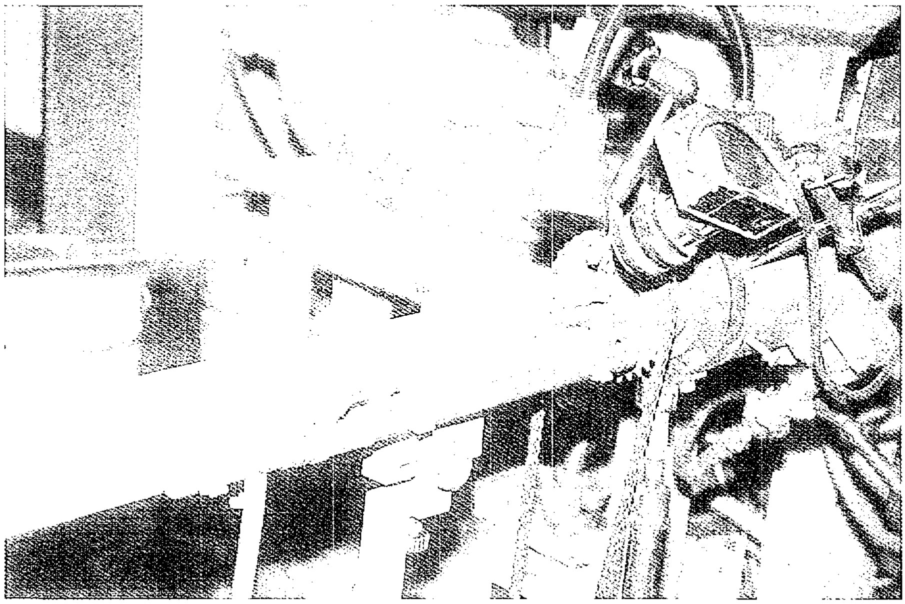

Figure No.11: patented procedure to produce helical twisted rods

This type of press can also be used very economically for the production of rods with parallel cooling ducts as well as solid rods without cooling ducts.
The plastification agent, which is to be dried out before the sintering, ensures that rods which can be subjected very easily to further shaping steps after the drying process and before the sintering are produced.

As an example, increasing numbers of rods are manufactured, which are already prefluted. Prefluting before sintering, which is very cheap, helps to avoid high costs for the grinding of flutes after sintering.
Cost savings of more than 30% in the production of ground tools are no rarity.

Figures No.12 and No. 13 show prefluted, unsintered tool blanks with remarkably sharp contours of the later cutting edges.

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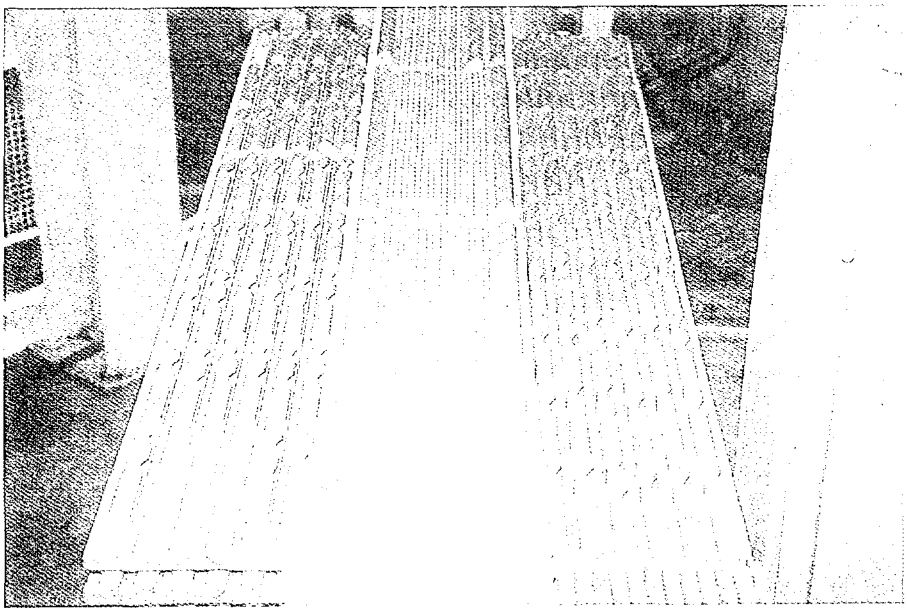

Figure No. 12: prefluted rods on sintering plates

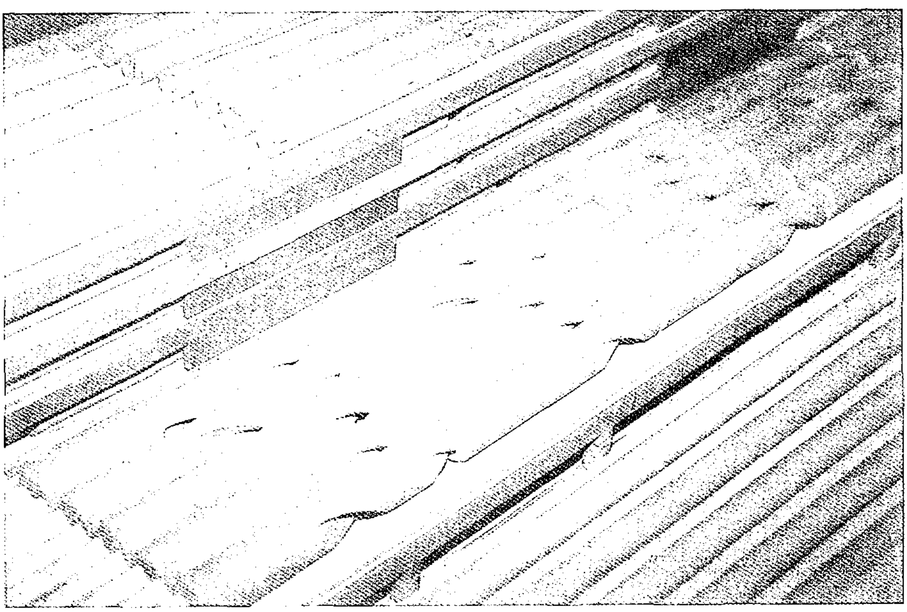

Figure No. 13: prefluted rods with clean edges

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No break-outs may be allowed to occur during hand shaping. A further growing program of sintered metal use is the field of paper knives and wood knives.
Soft paraffin is used primarily as the plastifier for the extrusion of small cross-sections in screw extruders.
The pressed molded parts are then stepped, although the cross-sections are small. With these small cross-sections, paraffin removal takes place in the sintering oven with no problem.

A typical press for the extrusion of rods of all kinds with low cross-sections in shown in Figure No. 14.
Presses of this kind have automatic cutting and transport fixtures for the rods and graphite carriers.

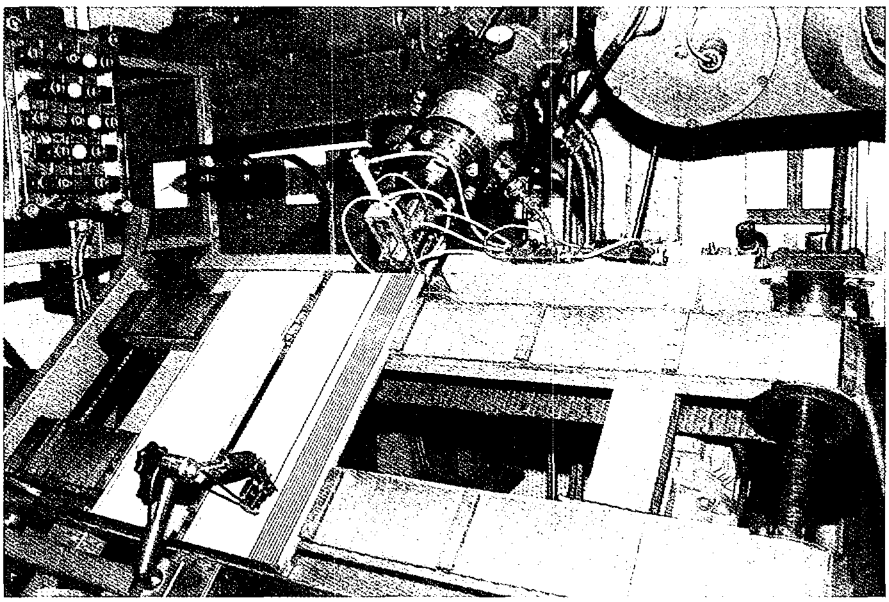

Figure No. 14: automatic press for rods with small cross-sections

Rods for the manufacturing of electronic drill bits have also experienced an upturn in recent years.

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Especially in the growth field of mobile telephones and personal computers, so many soldered points with the required drillings are necessary that the demand for such drill bits has risen sharply here.
These are drill bits with small diameters.
Diameters of 0.1 mm are no rarity thereby.
For a long time, drills were manufactured from carbide rods with a blank diameter of 3.25 mm. Nowadays, more and more bits which have a steel shaft with a diameter of 3.175 mm, into which a carbide pin of about 1.4 mm diameter is shrunk, are manufactured today. This pin is then ground down to the necessary outside diameter and given the spiral slots and front teeth.

The development of carbide types with finer and finer grain sizes was described in the previous chapter.
The production of rods with a blank diameter of 1.6 mm, for example, has been rationalized increasingly.
For this purpose, presses which do not always extrude only one rod at a time, but rather several rods simultaneously have been developed.
With the small diameters, this is necessary to obtain reasonably economic extrusion capacity.
The next figure (Figure No. 15) shows a press which extrudes and cuts 18 rods at a time and places them on the graphite carrier.

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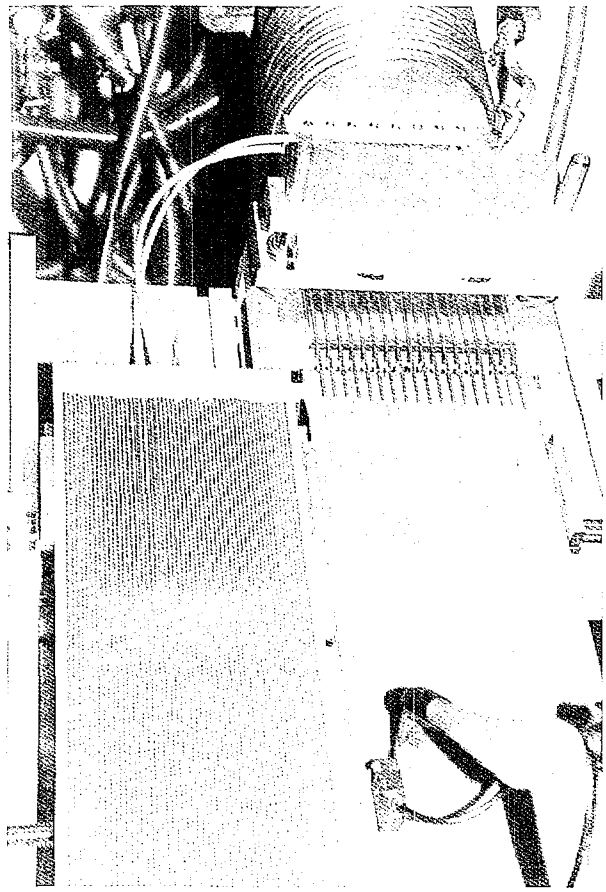

Figure No. 15: press for multiple rods in the same press cycle

The growing market for PC drills can be covered adequately only in this way.

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4.0 Outlook

The triumph of carbide has not come to an end. With increasing toughness and at least the same hardness, more and more areas which were previously reserved for HSS are being captured.
Special development trends are the use of finer and finer WC types, whereby variations of the cobalt content are made to influence the toughness.
Increasing attention is also devoted to the content of Cr_3C_2 and VC and the proportion of the two to each other.
The pressing process and tools are being rationalized further and further, whereby attention must be paid especially to screw extrusion processes with automation aids. The use of multiple nozzles will be forced.

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