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Diamond as a Wear-Resistant Coating

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Diamond as a wear-resistant coating

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Refractory chemical vapour deposition (CVD) coatings strongly improve the performances of hard metal tools. Low-pressure diamond synthesis permits both *in situ* CVD diamond coating and freestanding low-pressure diamond sheet fabrication. The performance of coated and freestanding bonded diamond layer tools approaches those of commercial polycrystalline diamond (PCD) products.

Low-pressure diamond grits and new composite powders could provide new and extraordinary grinding powders of raw materials for novel types of PCD composites.

Commercial production is now mainly a scaling-up problem. Reliable and low-cost fabrications are among the most important requirements. As these applications tolerate the use of polycrystalline layers, they are likely to be between those industrial low-pressure diamond products having soon a significant market share.

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1. Importance of the new diamond technology

(*a*) *Introduction*

Thin-film and coating technologies now used to produce diamond can lead to important improvements in industrial applications in many fields (Lux & Haubner 1992). If integrated into the function of a system, the lifetime and technical performance of the resulting components, such as tools, etc., can be significantly increased. For many applications the benefits obtained through thin films far exceed their manufacturing costs. Even if these costs are high, the resulting increase in performance of the components for their applications are justified by highly competitive improvements. Also novel diamond products, impossible to fabricate till now, can be expected from this new technology in the near future (Lux & Haubner 1989).

A few selected examples will illustrate the principles and possibilities of this new technology.

(*b*) *Industrial applications of wear-resistant surface layers*

1. Improvement of materials by hard chemical vapour deposition (CVD) and polycrystalline diamond (PCD) coatings are widely used today. Single-phase layers (such as Al_2O_3, TiC, TiN, Ti(C, N), HfN, etc. (Lux & Schachner 1978; Lux *et al.* 1971, 1989; Holleck 1986)) and multilayers (consisting of several single layers deposited sequentially, these are known as composite coatings) improved considerably many industrial cutting tool applications. Hard metals and ceramic materials are frequently used as substrates (Lux *et al.* 1987).

2. Superhard high-pressure products (i.e. PCD and polycrystalline cubic boron nitride (PCBN)) currently have a well-established market (Heath 1989). Their properties and performances under severe working conditions are generally

considered to be outstanding and highly competitive. They are the ultimate standard to be reached or, if possible, even to be exceeded by the new low-pressure diamond products now being developed.

Both PCD and PCBN are sintered products with appropriate amounts of a binder, and compacted at high temperatures and ultrahigh pressures. Frequently the PCD or PCBN layers are bonded directly to a hard metal substrate.

Applications of PCD tools (Heath 1989; Schweitzer 1989) are primarily in cutting, chipless forming, and wear part applications of abrasive workpiece materials such as: wood-based products; non-ferrous alloys (Al–Si, Cu, etc.); green ceramic and hard metals; abrasive reinforced plastics, man-made resin-bonded wood particle boards, plastic-laminated chip boards; stone and rock drills; wire-drawing dies; and other general applications of wear-resistant surface layers. Cutting speeds and conditions can be very high and severe (Ebberink 1991).

PCBN tools (Heath 1989) are preferably used for machining (turning, milling, boring, honing, etc.) and chipless forming of ferrous metals, such as nickel based superalloys (Inconel, Nimonic), gray and hard cast irons, hardened ferrous steels (greater than 45 R_c), special hard facing materials, etc.

Serious restrictions for certain wear applications exist.

(i) Ultrahigh-pressure technology leads to relatively expensive products.

(ii) Fabrication of three-dimensional (3D) shapes is limited and generally linked with time-consuming, complex, high-cost operations.

(iii) Because of the high-pressure technology all products have definite upper sizes and shape limits, which cannot be exceeded without prohibitive cost increases.

(c) *Conclusions*

Compared with the high-pressure techniques, the low-pressure approach offers more flexibility while remaining simpler, less expensive and appropriate for novel lower-priced mass production with good performances. New applications and broader marketing possibilities should result from this. Therefore the lower costs linked with equal, or even better, performances of the low-pressure technology as compared with the ultrahigh-pressure technology will be key factors.

2. State of the art

(a) *Low-pressure diamond layers as a challenge*

Property requirements of low-pressure diamond for wear applications

Superhard, wear-resistant protective coatings for tools and antiwear parts as well as decorative, scratch-resistant or corrosion-resistant surfaces need and utilize mainly the following outstanding properties of diamond: superhardness (high Young's modulus, rigidity, etc.); high degree of chemical inertness (antisticking surface, etc.); and high thermal conductivity.

These properties are relatively insensitive to lattice defects. Most applications tolerate polycrystallinity and even a certain amount of sp^2 bonding (Sato 1990) without major detrimental effects on the antiwear performances of the diamond. This greatly simplifies the development of industrial wear applications as compared with other uses (Badzian *et al.* 1987).

High quality low-pressure PCDs are facetted. Pure and binderless their crystal facets, orientation, internal defect structures, sp^2/sp^3 bond ratios and grain sizes can be controlled within certain limits by the synthesis parameters. Furthermore these

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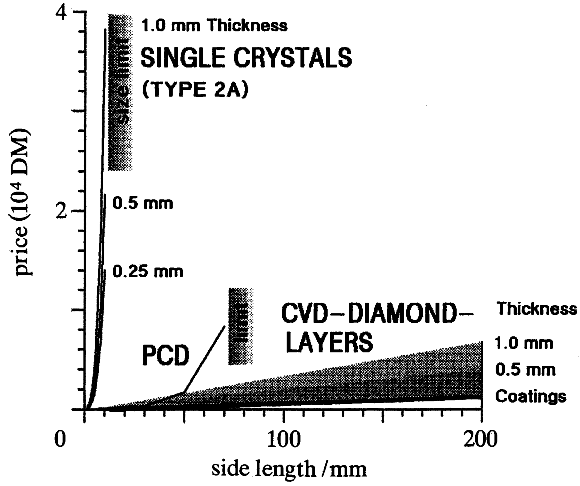

Figure 1. Comparison of the diamond price per surface area for different diamond products.

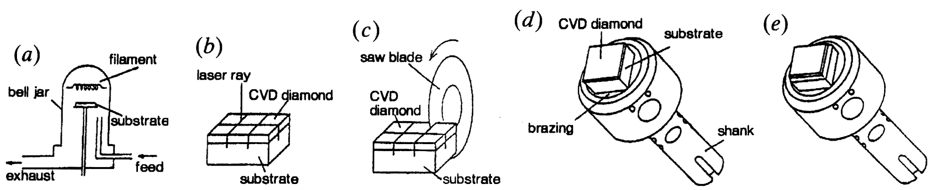

Figure 2. Production process of an *in situ* CVD diamond coated tool. An example is TAB bonding tool for micro electronics (Yashiki *et al.* 1991). (*a*) Synthesis of CVD diamond, (*b*) laser cutting, (*c*) saw blade cutting, (*d*) brazing, (*e*) CVD diamond TAB tools.

diamonds are available not only as bulky crystals but also in large two-dimensional shapes of defined thickness. Figure 1 shows a rough price comparison for different diamond qualities.

If used as an antiwear surface layer the low-pressure diamond permits the full utilization of diamond's extreme hardness, high modulus, thermal conductivity and other properties. The 'multilayer approach', today widely applied for conventional CVD cutting tools (Lux *et al.* 1987; Bichler *et al.* 1988; Schachner *et al.* 1984), should permit the development of tailor-made surfaces best suited for specific applications. It can also be applied to freestanding sheet products (Tanabe & Fujimori 1990).

Two different techniques are applied today for producing antiwear surface layers: *in situ* CVD coating (figure 2); and bonding of freestanding diamond sheets (figure 3). A technical comparison of these two products (figure 4) and the PCD products is given below.

In situ coating

Pros

(i) simple;
(ii) one-step operation for many substrates;
(iii) complex 3D shapes, due to high throwing power (tubings, dies, nozzles);
(iv) multilayers.

Cons

(i) chemical reactions of substrates with $C/H^0/H_2$;

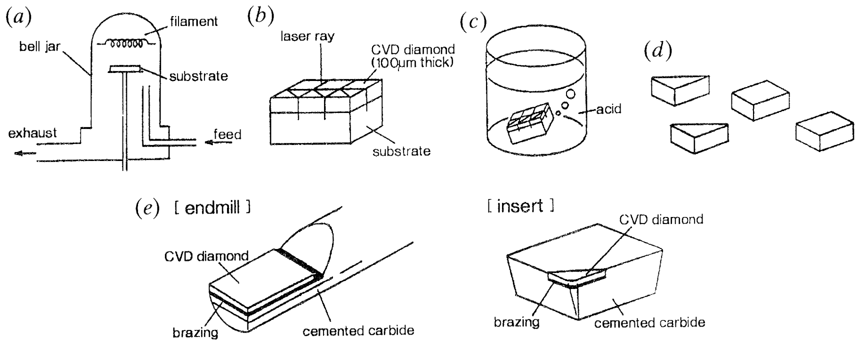

Figure 3. Production process of freestanding CVD diamond sheets brazed to cutting tools (Yashiki *et al.* 1991). (*a*) Synthesis of CVD diamond, (*b*) laser cutting, (*c*) dissolution of substrate, (*d*) freestanding CVD diamond pieces, (*e*) CVD diamond cutting tools.

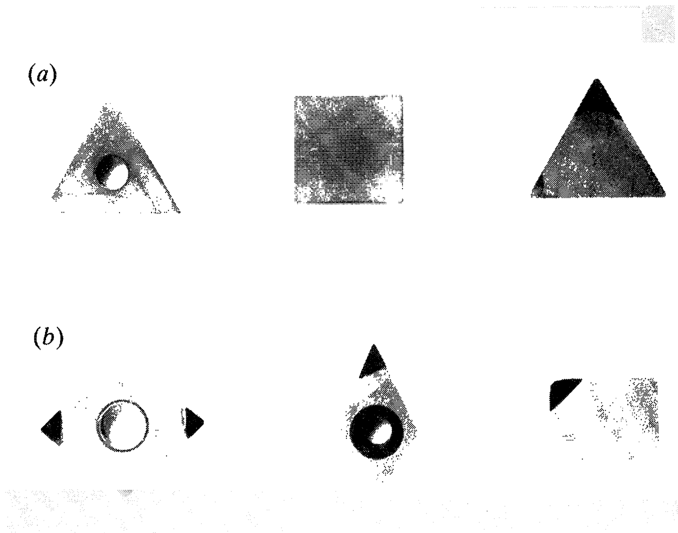

Figure 4. Examples of cutting tool inserts for metal cutting (Asahi Diamond Industrial). (*a*) *In situ* CVD coated, (*b*) tools with bonded freestanding CVD diamond sheets.

(ii) difficult adhesion with high expansion substrates;
(iii) rough as-grown surfaces;
(iv) substrate cooling for high growth rates.

Freestanding layer bonding

Pros (in comparison with *in situ*)
(i) separate processes for layer formation and bonding;
(ii) nucleation and growth on ideal substrates;
(iii) less interfacial stresses;
(iv) continuous production lines.
Pros (in comparison with PCD)
(i) binder-free;
(ii) large size sheets are no problem;
(iii) simple, inexpensive equipment;

Table 1. *Results of tool life tests and bonding cost analysis*

tool materials	CVD diamond	sumicrystal	PCD1	PCD2
tool life ($\times 10^3$ shots)	600	2000	200	80
maximum regrinds	—	3	3	3
total tool life ($\times 10^3$ shots)	600	8000	800	320
tool price (CVD unit base)	1	2.5	1	1
regrinding price (PCD unit base)	—	2.5	1	1
bonding cost (CVD unit base)	1	1	3.2	2.9

(iv) easy control of grain sizes, structure, etc.;
(v) multilayer sheets, allowing grades.

Cons (in comparison with *in situ*)
(i) only flat or simple 3D shapes;
(ii) many production steps (dummy surface preparation, diamond sheet fabrication, cutting, brazing to the tool, final grinding and polishing operations)

Cons (in comparison with PCD)
(i) grade nuances (due to missing binder)

(*b*) *Potential products and industrial applications*

In situ CVD *diamond*

TAB (*tape automated bonding*) *stamps*. These are used in microelectronics to connect chips to wires and circuits (Yashiki *et al*. 1991; Sumitomo Electric Industries 1990).

Recently, there has been a large demand to increase the through-put for flat packaging (identity cards, calculators, liquid-crystal displays, etc.) and to decrease production costs. The TAB process is now accepted by many electronic goods suppliers. During bonding the tools are heated to 500–600 °C and pressed down by a load.

CVD–TAB tools are special ceramics coated with a 50 μm thick hot-filament CVD diamond layer (figure 3). The diamond surface is polished until its surface roughness is less than 0.1 μm.

Both flatness and wear resistance tests of TAB tools are very important (Yashiki *et al*. 1991).

Technical results

Cleaning damage to CVD diamond is less than that of PCD, and CVD diamond showed a resistance as single crystalline diamond. As well as the economic advantage, low-pressure diamond further offers the possibility of producing much larger tool sizes than single-crystalline high-pressure diamond (Yashiki *et al*. 1991).

Cost assessment and lifetime

1. Cost per bond (including regrindings) for both CVD diamond tools and single-crystalline tools are considerably lower than those of PCD (table 1).

2. Single crystalline tools have the longest lifetime (eight million individual bonds) but high initial costs. They are most suitable for mass production with only slight variation in design.

3. CVD diamond and PCD tools show almost the same lifetime (several hundred thousand shots). They are best suited for medium-variety and medium-quantity or large-variety and small-quantity productions.

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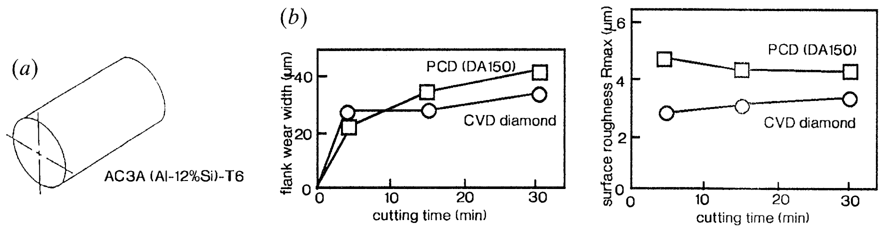

Figure 5. Comparison of flank wear width and surface roughness during dry continuous-cut turning. (*a*) Work piece, (*b*) results (Yashiki *et al.* 1991).

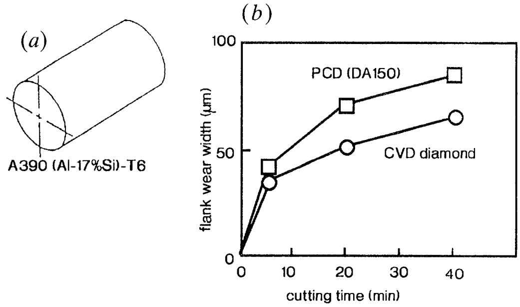

Figure 6. Comparison of the performance of PCD and CVD diamond layers during wet continuous-cut turning. (*a*) Workpiece, (*b*) results (Yashiki *et al.* 1991).

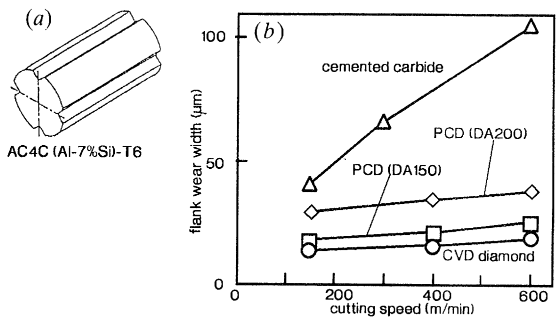

Figure 7. Comparison of the performance of hard metal and different diamond qualities during interrupted-cut turning. (*a*) Workpiece, (*b*) results (Yashiki *et al.* 1991).

Metal cutting tools

Continuous (turning) and interrupted cutting (milling) of Si rich hypereutectic Al–Si alloys under wet and dry conditions were examined recently by a number of research groups (Lux & Haubner 1989; Oakes *et al.* 1990; Yashiki *et al.* 1991).

Cutting performances of CVD diamond coated tools are excellent (figures 5–7) in comparison with hard metals; PCD can be reached in many cases (Yashiki *et al.* 1991; Sumitomo Electric Industries 1990).

Face milling and other factory machining tests. These showed that CVD diamond coated inserts can perform much better than hard metals (Yashiki *et al.* 1991). Also face milling of ceramic workpieces, copper alloys, graphite boards and wear-resistant grinding wheels was excellent (Kikuchi 1989).

Microdrills and twist-drills. These are made of hard metals (figure 8) are of great potential interest but more difficult to achieve.

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Figure 8. Microdrill *in situ* coated with CVD diamond (Asahi Diamond Industrial).

Industrial endmills and metal-cutting tool inserts. Those using bonded free-standing CVD diamond (figure 3) have been commercially available for a few years. They are simple to produce and have no cobalt or other binders in the diamond sheet, which is an advantage over PCD. During machining of copper-coated printed circuit boards (GFRP) they revealed clear superiority over hard metals. Tool life can be improved more than 10 times. Figure 9 shows the low flank wear observed with a diamond surface as compared with that for conventional hard metal endmills.

(*c*) *Conclusions*

Both techniques, *in situ* and bonded free standing layers, have their technological advantages and disadvantages which influence their price and their performance (see above). (For example, *in situ* diamond-coated cutting tool inserts, as well as free-standing endmill tools, are between those of PCD and hard metal tools and sometimes even superior to PCD.) It must be stressed that such test results are only excerpts from current research projects. Until now most results were obtained with specimens from experimental laboratory units (fewer than 20 specimens) or small prototype reactors (up to a few 100 specimens). Further important improvements in performance can be expected through an optimization of adhesion by a controlled substrate surface chemistry (surface preparations, minimized internal and interfacial stresses), and optimized coatings (structure, thickness, grain size, surface roughness, etc).

3. Technological gaps and currently unsolved problems

(*a*) *Problems related to fabrication and adhesion*

Influences of substrate chemistry, nucleation and growth.

Diamond nucleation on highly perfect substrate surfaces, for example silicon wafers, is sluggish and starts only after a long initial time period. Nucleation is also difficult if the surface carbon concentration is lowered rapidly by diffusion into the substrate (Lux & Haubner 1991).

Chemical reactions occurring between substrate and reaction gas (carbon, atomic and molecular hydrogen) can have an important influence on nucleation and adhesion (Lindlbauer 1989).

Nucleation enhancements, such as scratching the substrate surface with diamond powders, are generally effective in enhancing the diamond nucleation density (Lux & Haubner 1991). Without such enhancement it can be a major problem to obtain very thin coatings. Thick layers having facetted diamonds can lead to important

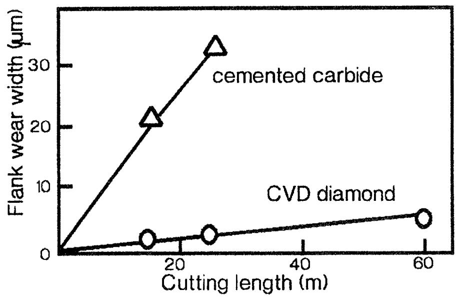

Figure 9. Wear resistance of double-flute CVD diamond endmill (Yashiki *et al.* 1991).

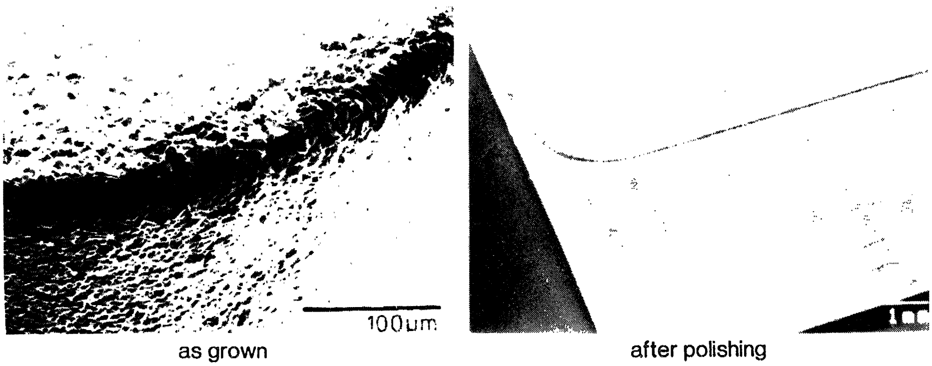

Figure 10. Roughness of CVD diamond. Coated cutting edge before and after polishing (Asahi Diamond Industrial).

surface roughnesses, undesirable for many applications. Costly grinding and polishing operations can become necessary (figure 10).

Fundamental problems of adhesion

Bad adhesion is frequently strongly associated with interfacial stress, which depends primarily on the different expansion coefficients of layer and substrate. Also excessive internal layer stress is important (Reineck *et al.* 1990).

The simple linkage of the substrate surface temperatures during deposition and the expansion coefficients of different substrates are shown in figure 11. It was shown recently that lowering the surface temperature during diamond deposition on hard metal tools can improve adhesion of the coating (Oakes *et al.* 1990). A strong chemical bonding between diamond and the substrate material is necessary for achieving the bondstrength needed for CVD coatings of cutting tools. Although the reproducibility still has to be improved, some diamond-coated substrates are already able to achieve the required excellency in adhesion for acceptable performances (see §2*b*).

However, chemical interactions leading to formation of solid intermediate layers or gaseous species can also be detrimental (Reineck *et al* 1990; Lux & Haubner 1991; Lindlbauer 1989).

(*b*) *Synthesis methods and industrial fabrication units*

Though during the past few years a large number of different new methods for low-pressure diamond deposition have been developed (Lux & Haubner 1992), mass production of *in situ* and freestanding layers for tools and wear applications still

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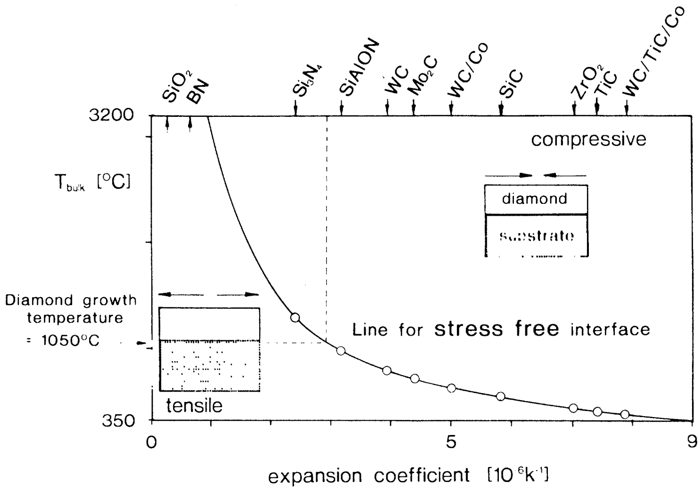

Figure 11. Influence of temperature and expansion coefficients on interfacial stress at a constant substrate surface temperature of 1050 °C (Lindlbauer 1992).

requires scaling up of the reactors. The most important technical factors for the choice of the synthesis method for industrial production are the reliable control of the deposition process (so as to obtain a constant and reproducible high-quality diamond) as well as the economy of the process. Size and shape of the products will largely determine the production units.

The following discussion considers mainly the problems of small mass products such as indexible inserts for cutting tools. In principle either a method with extremely high local growth rates (i.e. small deposition area), or a method that has a sufficiently large deposition surface/volume, with only a moderate local growth rate, can be chosen.

For *in situ* coating, in batch-type production reactors with low growth rate diamond methods, the deposition area must be large enough to ensure a reasonably high throughput. Only if the diamond growth rates are very high can shorter deposition times become possible, so that continuous production units might be feasible.

However, for reasons of control and reproducibility, lower growth rate methods seem preferable, as they allow an easier control of the diamond quality. Currently, hot-filament and microwave gas activation methods fulfill these requirements best and are now generally considered to be the preferred choice for scaling up units for the above products.

High growth rates are obtained with jet methods, such as plasma arc jets or the surprisingly simple oxygen/acetylene flame, both of which can work at atmospheric pressure. Deposits of high-quality diamonds were obtained with both methods.

The interesting synthesis possibility of halogenides was recently demonstrated (Patterson *et al.* 1991; Rudder *et al.* 1991) but is not yet well enough described for conclusions to be drawn. These methods could have a greater potential for inexpensive diamond grit.

Freestanding layers could be produced by both batch-type and continuous units. Most of the above considerations for *in situ* diamond production are also valid for freestanding layers, with the extremely important exception that for freestanding layers the optimal substrate for nucleation and growth can be freely choosen. ‘Ideal

Table 2. *Comparison of the specific energy* (kWh g^{-1} *deposited*) *for a high- and a low-growth rate method of diamond deposition*

	microwave	arc jet
methane flow/($cm^3\ s^{-1}$)	1	80
power/kW	1	9.5
deposition rate/(μm h^{-1})	1	500
deposition area/cm^2	20	0.1
carbon supplied/(g h^{-1})	0.032	2.6
carbon deposited/(g h^{-1})	0.0071	0.0176
carbon conversion efficiency (%)	22	0.68
specific yield/(kWh g^{-1})	140	540

substrates' can be used because interface bonding requirements between dummy and diamond are much less critical than for the *in situ* coating and thus much easier to meet. Freestanding sheet materials are simply cut to the required shape and size needed for the final superhard surface before bonding.

Economical, continuous high-speed production of diamond-coated dummies can be envisaged, with diamond synthesis methods having high growth rates if several deposition sources are applied consecutively.

For thick sheets, highly polished dummy surfaces can produce a smooth replica diamond surface which can be used directly if the interface is turned inside out and used as the working surface. In connection with precision bonding it could minimize or possibly avoid the costs of the final grinding of the tool.

(c) *Economic considerations*

Whichever method is used it must fulfil not only the technical requirements noted above but also the economic ones. Despite the large number of methods available, the choices for industrial production methods are limited if economic and technical requirements are taken into account. Critical evaluations of the raw materials and the energy yielded, as well as the costs of the investments and labour are necessary. A comparison of two concepts for applying low-pressure diamond is given in table 2. An exact assessment demands a thorough knowledge of the processes and such information is still scarce. Recently L. K. Bigelow (personal communication) pointed out the importance of the specific energy per carat deposited. Comparing the two representatives of a high-growth and a low-growth rate method, he came to the conclusion given in table 2. Such important methods as hot-filament, DC plasma and flames are unfortunately not included in their considerations. It is clearly too early to give a full economic evaluation here.

4. Market potentials and future prospects

(a) *Market potential*

Figure 12 shows the potential market for CVD diamond products for the year 2000. According to this estimate, from a total market of \$6500 M, thin-film products (*in situ* CVD coatings) will account for \$4500 M and the thick-film diamond products (freestanding films and sheet materials) are expected to amount to \$2000 M. Applications for wear parts, material-removal products and abrasives will be the most important markets sectors for CVD diamond in the near future.

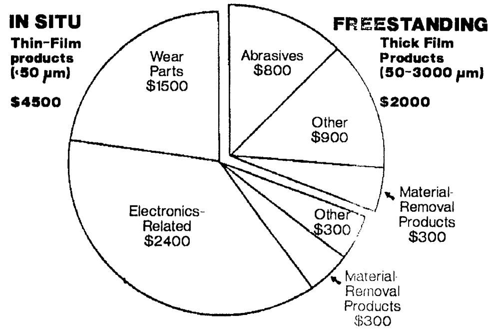

Figure 12. The potential market for CVD diamond products for the year 2000 (in million US dollars) (Genasystem 1990).

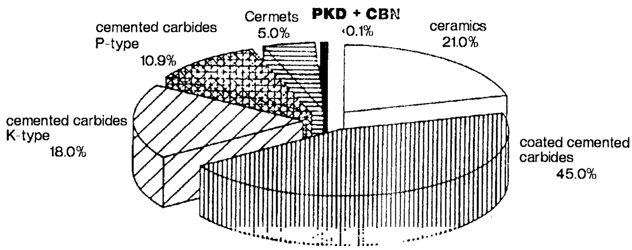

Figure 13. Typical distribution of cutting tool materials used in a modern automotive industry (Johannsen 1989).

The modern automotive industry is a good example of industrial demands (Johannsen 1989). Si-rich hypereutectic Al–Si alloys, used more and more for engine parts, have to be turned, milled, honed, etc. These specific applications are taken as an example and commented briefly in the following. Figure 13 shows that currently normal PCD and PCBN materials represent together just a small fraction (less than 0.1%) compared with the other tool materials. The high percentage of CVD or PCD coated hard metal tools (multilayers of TiC, TiN, Al_2O_3, etc.) compared with the uncoated tools demonstrates the enormous impact the *in situ* CVD coating has had on tooling applications since it was first applied some 20 years ago (Lux & Schachner 1978).

Although the performance standard of PCD products is undoubtedly the goal to be reached, the object is not merely substitution of these products. To reach the full potential of CVD diamonds, much broader use is needed.

The future market share of low-pressure diamond cutting inserts and other tools will thus be based mainly on the technical advantages of the CVD technology, such as allowing the realization of more complicated tool shapes (J. Motzet, personal communication). In combination with the well-known benefits of PCD products there is a wide field of new market opportunities.

In the end, the decisive reason for a mass producer to choose low-pressure diamond tools will be the lower global costs per piece produced.

In this case the tool costs themselves are not the most important. A tool with the superiority of pure diamond – having a much greater lifetime and giving excellently machined surfaces with exact tolerances – means more reliable products with less efforts in man power.

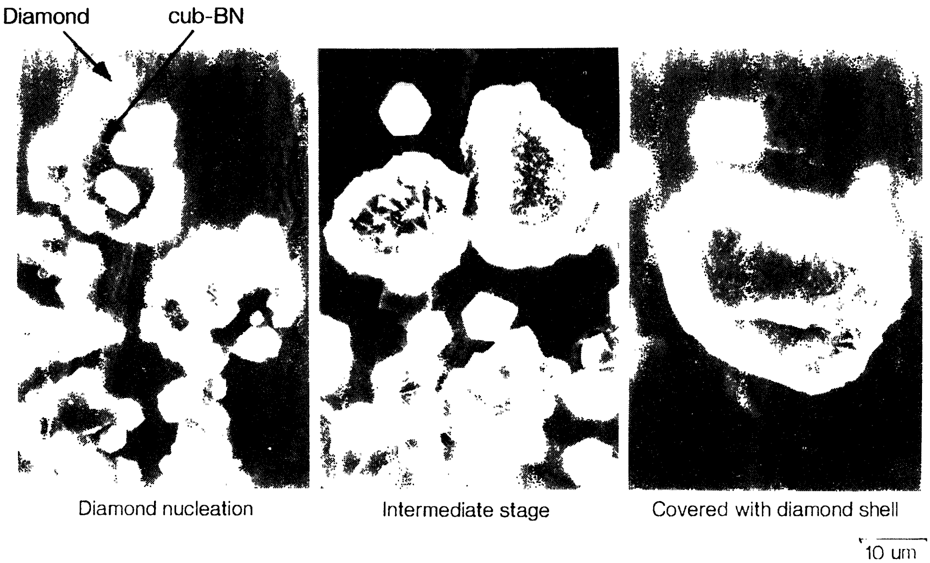

Figure 14. Different stages during production of a diamond composite powder (cub-BN core covered with a diamond shell (Haubner 1990, Lux 1986).

Moreover, significantly higher cutting speeds and the higher chip volume produced per tool save production time per piece manufactured. They permit a more efficient use of highly complex, automatized and expensive machines by reducing their non-productive time periods (less downtime for replacements of tools, adjustments, maintenance, etc.). This also lowers the investment costs for equipment and capital costs for building. Thus an enormous amount of money is free to pay for excellent tools that can substantially reduce production costs (J. Motzet, personal communication).

(b) *New superhard composite powders and compacted products*

Abrasive natural or high-pressure diamond powders have always held an appreciable share of the world's diamond market. Low-pressure diamond could become a competitor in future. Low cost production chemical processes, such as the recently discovered halide synthesis methods (Patterson *et al.* 1991; Rudder *et al.* 1991), might be of great interest.

Recently the feasibility of diamond 'composite powders', which consist of hard particles enveloped by a low-pressure diamond coating was demonstrated (figure 14). Such powders permit combinations of materials previously impossible to realize. Besides their use as abrasives, composite powders mixed with binders, compacted and sintered at ultrahigh pressures, or even conventionally compacted at low pressures by a classical sintering operation, could result in exciting, novel PCD-type products. Since abrasive products are relatively inexpensive, a low-pressure powder fabrication in large reactors (Litos 1992) with excellent yields is required to bring the production costs down to competitive levels. However, materials with outstanding properties and performances usable for unique, sophisticated applications are not subject to stringent price limitations (Lux 1986).

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(*c*) *The superhard BN phases*

Many analogies exist for the boron nitride materials. The superhard BN phases are extremely interesting for wear applications. The offer an alternative set of diamond's chemical properties in such applications. As discussed for diamond, utilizing mainly the superhardness means that polycrystallinity and lattice imperfections are acceptable. Therefore, once appropriate low-pressure synthesis methods are established, the wear applications of coated BN tools are likely to be the initial commercial products.

Until now, however, attempts to synthesize cubic BN at low pressures have not been as successful as those to produce low-pressure diamond. Major basic problems have apparently not yet been satisfactorily solved (Rödhamer 1989). A direct analogy to the low-pressure diamond CVD synthesis appears to be an obvious possibility, however.

The recent annual market growth rates of superhard products were high and are projected to increase during the next couple of years. Superhard BN films and coatings should rapidly gain significant industrial importance, as BN exhibits an excellent inertness to hot steel surfaces under conditions where diamond is violently dissolved and therefore cannot be used. As known from the ultrahigh-pressure PCBN, this fact alone promises extraordinary possibilities for tools for shaping steels. In view of this potential market for highly relevant commercial applications, more and more research groups are working on the low-pressure CVD synthesis of superhard BN (Rödhamer 1989).

Besides the synthesis of the pure BN phases, the combined synthesis of diamond and BN could lead to new superhard materials with interesting properties complementing those of pure diamond and pure BN (Lux 1986; Badzian 1988).

5. General conclusions

Wear and cutting applications mainly utilize the superhard properties of diamond. Today, product development for these applications has already reached a relatively advanced stage, since single crystallinity and a perfect diamond crystal lattice are not primary requirements for their proper functioning.

Though their technical feasibility has been demonstrated and has already led to some industrial products, the production of technically and economically feasible products for superhard applications is still only in its early stages. The rapid advancement in these 'simpler' application areas will most certainly continue and even gain momentum.

Beside improving problems of economy, major technical problems, such as *scaling up* remain unsolved. A number of individual, as yet unpublished, larger-scale production setups are now being simultaneously developed. The selection of the 'best' method, determine the construction of the most suitable equipment for specifique products is the big challenge at present. The CVD reactor for normal hard coatings is traditionally a batch-type unit. It seems that the initial *in situ* coating unit for low-pressure diamond coatings will be the same for both *in situ* and freestanding diamond products.

Though successful performance tests are encouraging and prove that the diamond coating adhesion for *in situ* coatings and freestanding diamond layers is not an insoluble problem, better adherence and general reproducibility are needed. Selection of the appropriate substrate chemistry or effective multilayer combinations can help to reduce interfacial stress.

Methods for a well controlled diamond nucleation, combined with reproducible substrate surface preparations, will help to achieve this goal.

Other important topics are composite powders as well as compacted products from such powders. Their future depend largely on their properties, on new applications and on their production costs.

Synthesis of superhard boron nitrides or other new superhard phases are still in the basic research stage. Both are an exciting challenge for the near future, especially in view of the considerable market potential of these materials for wear applications.

References

Badzian, A. R. 1988 *Advances in X-ray analysis*, vol. 31, pp. 113–127. New York: Plenum.

Badzian, A. R., Bachmann, P. K., Hartnett, T., Badzian, T. & Messier, R. 1987 In *Proc. E-MRS Meeting*, vol. XV, pp. 63–77. Les Editions de Paris.

Bichler, R., Peng, J., Haubner, R. & Lux, B. 1988 *Mater. Sci. Engng* A **105**, 543–547.

Genasystem Worthington, Ohio; Materials and Processing Report, vol. 5, No. 4/5 Elsevier.

Haubner, R. 1990 *J. Ref. Met. Hard Mat.* **9**, 70–77.

Heath, P. J. 1989 *VDI Berichte* **762**, 37–59.

Holleck, H. 1986 *Z. f. Werkstoffk.* **17**, 334–341.

Johannsen, P. 1989 *VDI Berichte* **762**, 259–271.

Kikuchi, N. 1989 *Diamond and DLC coatings*. Marco Island, Florida: Gorham Advanced Materials Institute.

Lindlbauer, A. 1992 Doctoral thesis, TU-Vienna, Austria.

Litos, R. 1992 Doctoral thesis, TU-Vienna, Austria.

Lux, B. 1986 European Patent, EP 0226898 A2.

Lux, B., Funk, R., Schachner, H. & Triquet, C. 1971 CH Expose d'Invention, 540990.

Lux, B. & Schachner, H. 1978 *High Temp. High Press.* **10**, 315–323.

Lux, B., Haubner, R., Altena, H. & Colombier, C. 1987 Fischmeister/Jehn. *Hartstoffschichten zur Verschleissminderung*, pp. 71–112. Oberursel, Germany: Verlag.

Lux, B., Haubner, R. & Wohlrab, C. 1989 *Surf. Coatings Technol.* **38**, 267–280.

Lux, B. & Haubner, R. 1989 *RHM* **8**, 158–174.

Lux, B. & Haubner, R. 1991 Diamond and diamond-like films and coatings. In *Proc. NATO-Advanced Study Inst. on Diamond and Diamond-Like Films and Coatings* (NATO-ASI Series B: Physics), vol. 266. New York: Plenum.

Lux, B. & Haubner, R. 1992 In *Diamond films and coatings* (ed. R. Davies). New Jersey, U.S.A.: Noyes.

Oakes, J., Pan, X. X., Haubner, R. & Lux, B. 1990 In *Proc. 1st Euro. Conf. on Diamond and Diamond-like Carbon Coatings* (ed. A. Matthews & P. K. Bachmann), pp. 600–607. Crans-Montana, Switzerland.

Patterson, D., Clin, J., Bai, B., Xiao, Z., Tomplin, N., Margrave, J. L. & Hange, R. 1991 In *Proc. 179th Meeting of the Electrochemical Society*. Washington, D.C.: U.S.A.

Reineck, I., Söderberg, S., Westergren, K. & Shahani, H. 1990 In *Proc. 2nd Int. Conf. on the New Diamond Science and Technology* (ed. R. Messier, J. T. Glass, J. E. Butler & R. Roy), pp. 809–814. Washington, D.C., U.S.A.

Rödhamer, P. 1989 In *Proc. 12th Int. Plansee-Seminar* (ed. H. Bildstein & H. M. Ortner), vol. 3, pp. 661–667. Reutte, Austria.

Rudder, R. A., Thomas, R. E. & Markunas, R. J. 1991 In *Proc. 179th Meeting of the Electrochemical Society*. Washington, D.C., U.S.A.

Sato, Y. 1990 In *Proc. Workshop on the Science and Technology of Diamond Thin Films*. Cleveland, Ohio.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Schachner, H., Tippmann, H., Lux, B., Stjernberg, K. & Thelin, A. 1984 Swedish Patent 8403428.

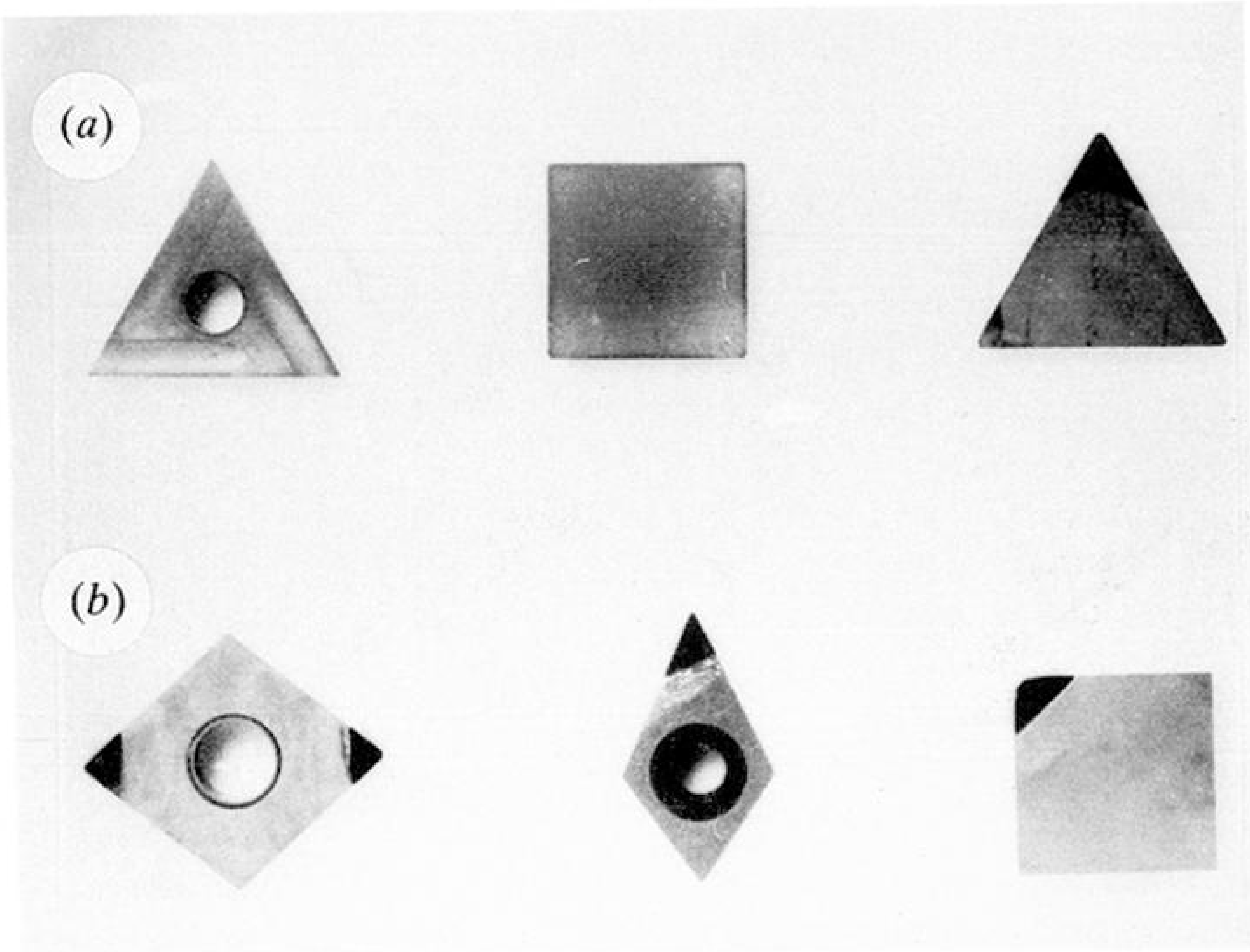
Schweitzer, R. 1989 *VDI Berichte* **762**, 293–303.

Sumitomo Electric Industries 1990 TAB bonding tool, EV-32R (August 1990) (commercial documentation).

Tanabe, K. & Fujimori, N. 1990 Japanese Patent Application, Tokugan-hei 2(1990)-81777.

Yashiki, T., Nakamura, T., Fujimori, N. & Nakai, T. 1991 In *Proc. Int. Conf. on Metallurgical Coatings and Thin Films*. San Diego, California.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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gure 4. Examples of cutting tool inserts for metal cutting (Asahi Diamond Industrial). (*a*) *In situ* CVD coated, (*b*) tools with bonded freestanding CVD diamond sheets.

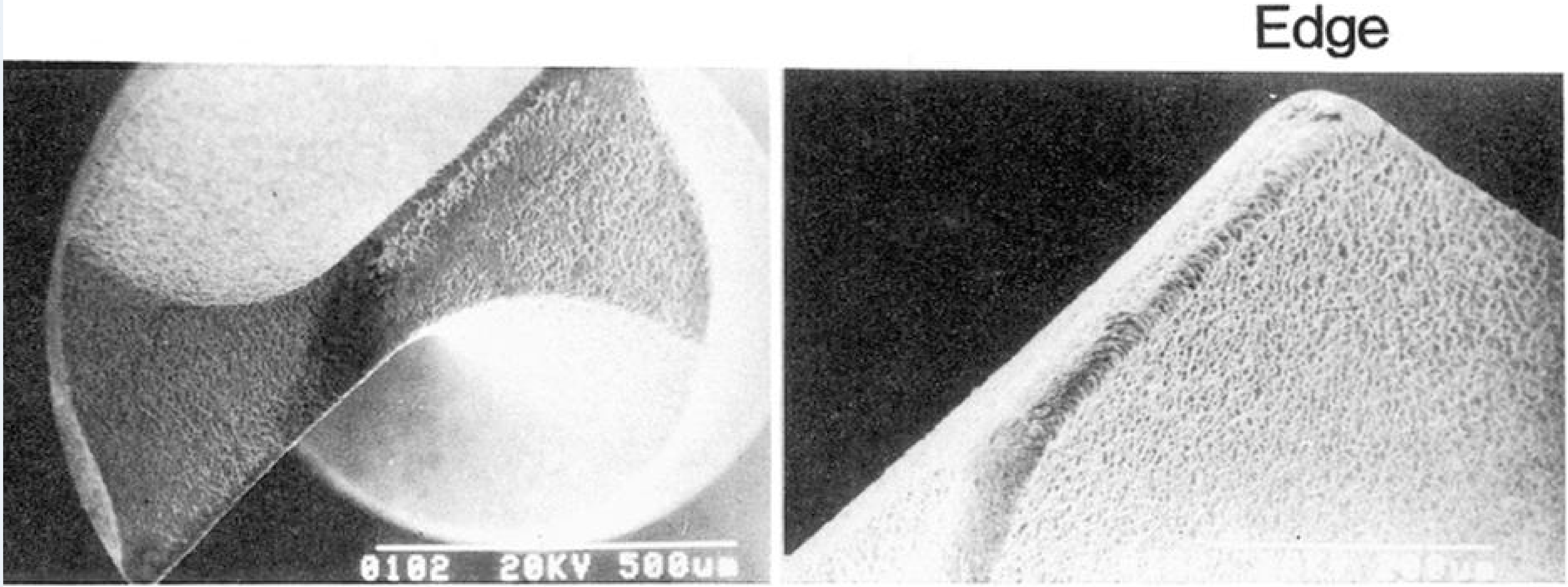


Figure 8. Microdrill *in situ* coated with CVD diamond (Asahi Diamond Industrial).

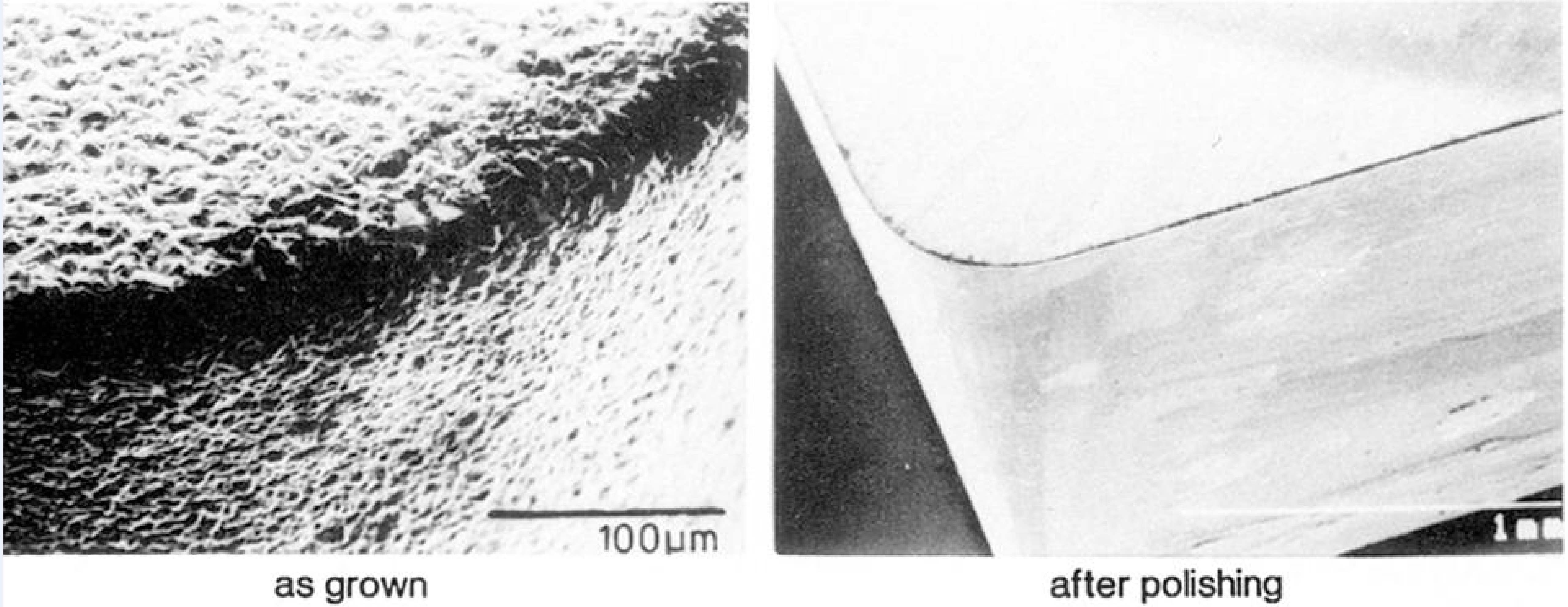
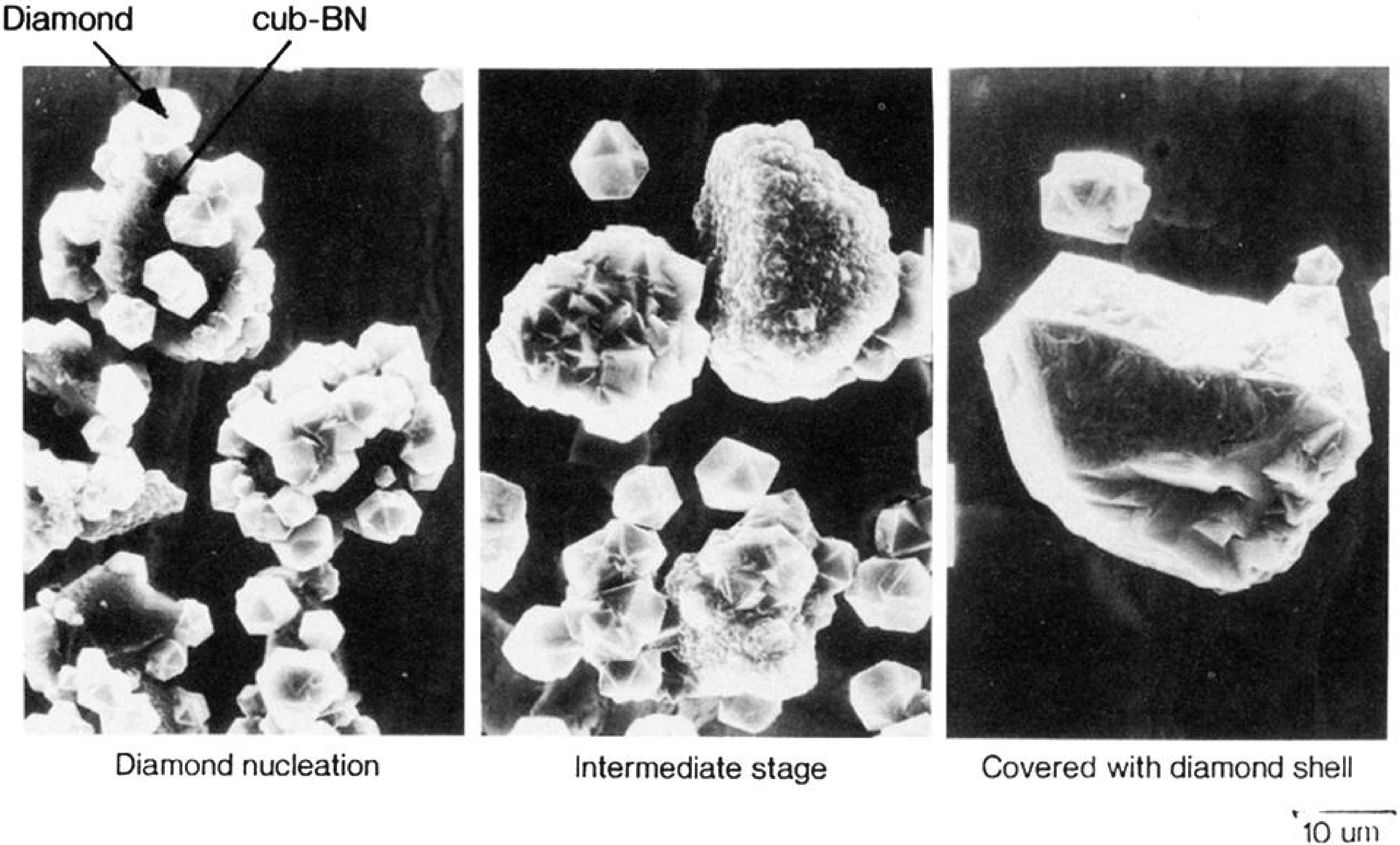


Figure 10. Roughness of CVD diamond. Coated cutting edge before and after polishing (Asahi Diamond Industrial).



igure 14. Different stages during production of a diamond composite powder (cub-BN core covered with a diamond shell (Haubner 1990, Lux 1986).

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