

Copy for Tracy Hall  
Comm. Fig. 4-1

"The Uses of Synthetic Diamond and Cubic Boron Nitride  
in Industry and Technology"

(Talk for American Physical Society, March 22, 1977)

- R. H. Wentory part.

As you all know, it is nice when now and then some products of the scientific laboratory are actually used for practical purposes. The unique properties and relative scarcity of diamond made its price high enough to ease the task of finding economically acceptable methods for large-scale production of synthesized diamond. An additional favorable factor was the discovery that the crystal morphology of the diamond affects its utility, and that this morphology could be pretty well controlled during growth.

For example, a lot of diamond abrasive is used to grind cemented tungsten carbides, as depicted in Figure 4-1; these carbides are used for a wide variety of high-productivity tools in industry. The kind of diamond which does this job the best has an appearance which a crystal-grower or solid-state physicist would regard as terrible: it's full of fissures and overgrowths and inclusions, as you can see in Figure 4-2. When such crystals are bonded into an abrasive wheel, usually by means of a high-melting resin or a low-melting ceramic, the rough crystal surfaces help to hold the crystals in the wheel as they cut on the workpiece. When the cutting edge of a crystal becomes dull, the forces on it increase. If the crystal were strong, it would be torn from the wheel and its useful life would be finished. But if the crystal is not too strong and is firmly held, the dull edge portions will chip off and newly-formed sharp edges will be formed to continue cutting. Thus the usefulness of the diamond grain is increased. It is necessary to have a true cutting action here because the workpiece material is ductile and strong in tension, and so it can't be cracked out very easily. If the cutting edge becomes dull and cutting action is replaced by a sort of plowing action, excessive heating by friction occurs locally and the resulting higher temperatures favor chemical attack or graphitization of the diamond.

all figures referred to in text with prefix 4-  
figures in some may be labeled 4.

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Another large use for diamond abrasive is sawing or grinding stone, concrete, glass, ceramics, etc, as shown in Figure 4-3. You might think that the same principles about cutting action would apply to this use as they did for cemented tungsten carbide. In the beginning you would be right. Figure 4-4 shows some curly glass chips cut from the surface of a microscope slide by the sharp edges of diamond grains. But the cutting edges soon become dull and a kind of plowing action then occurs in which the workpiece material fails in tension near the advancing abrasive grain. If the grain is strong, it can continue to plow for a long time with satisfactory results, basically because the workpiece material is weak in tension. Some of the tough, strong diamond crystals useful for cutting ceramics, glass, rock, etc. are shown in Figure 4-5.

As Herb Strong mentioned, the sizes and crystal morphology of the synthesized diamonds can be controlled by the conditions of growth, and so the manufactured diamonds are tailored to the end uses, with several kinds of diamond available in appropriate sizes. In this way the most effective and economical use of diamond is obtained, and the average improvement in the performance of diamond abrasive is approximately a factor of two from the time when the synthesized diamonds first appeared on the market, about 20 years ago. The bulk of abrasive diamond use is now met by synthesized diamond, hundreds of kilograms per year. In spite of the improvements in performance, the price of diamond abrasive has remained about the same, \$2.75 per carat or \$6000 per pound.

Not all industrial diamond is used as abrasive, however. Respectable amounts are used as single crystals, of gemstone size, in special cutting tools, rock drills, wire-drawing dies, and tools for dressing grinding wheels. However, single crystal diamond is easily cleaved on planes parallel with the octahedral faces, and this characteristic of diamond generally acts to shorten the life of tools made from single crystals. Some natural polycrystalline lumps of diamond known as carbonado can be found in Brazil and western Africa where the two continents were once joined. These lumps are

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much tougher than single crystals but the supply is limited and the quality is uneven. For many years a goal of diamond research was to sinter small diamonds together into strong pieces.

Some formidable natural obstacles stand in the way to this goal. First of all, glueing the diamonds together with some sort of a bonding agent is not a satisfactory solution. The strength, melting point, and thermal conductivity of diamond are so far above those of any potential glue that the composite would have properties more like the glue than like diamond. Many investigators will agree on this point, having worked over all the glues they could think of. The best glue is diamond itself, that is, the crystals must be held together by direct diamond-to-diamond bonds.

Second, the sintering process has to be carried out at some temperature where the carbon atoms are somewhat mobile, which implies a high pressure, otherwise the diamonds will change to graphite. Getting a high pressure all around a diamond crystal is not so easy in a mass of diamonds. If you put some diamonds in a box and squeeze on the sides, you do not move the diamonds together very much because they are so hard and strong. Many voids remain among the grains. If you squeeze harder, the diamonds simply indent the walls of the box. It is like trying to compress a mass of sand inside a box made of modeling clay. Where the diamond grains touch each other, the pressures are quite high, and where they don't touch, the pressures are quite low, a few atmospheres. If the mass is heated, graphite can form where the pressure is low. In order to change this graphite back into diamond, it has to be subjected to fairly high pressures, but the pressure won't be there unless the grains which are supporting the compressive load deform. But these grains are the strongest material known.

From the foregoing remarks one might conclude that sintered diamond masses are almost impossible to make except at pressures and temperatures like those used by Bundy to transform graphite into diamond, say 130 kbar and 3000°C. If natural carbonadoes formed in this way, one must regard them as very special visitors to the surface of the earth, because 130 kbars corresponds to a depth in the earth

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of about 400 km or 250 miles.

Tracy Hall found that 130 kbar was not needed to make something useful out of diamond powder. He used 70 kbar or so and controlled the time and temperature so that only small amounts of graphite formed while the diamonds were hot enough to stick together where they touch each other. You might call this a pure physics approach to the problem.

Meanwhile, in our lab at G.E. we thought we'd try a little chemistry, too, if you'll pardon the thought, and we found a way to make sintered diamond masses which are extremely thoroughly bonded by diamond-to-diamond bonds, with no graphite and only a little metal in the mass. The main fault of such lumps appears to be that they are so strong and hard that they take almost forever to shape and polish, even on a diamond lap. They are now manufactured in several shapes, some of which are shown in Figure 4-6. Figure 4-7 shows the polished surface of such a diamond mass and reveals the extensive diamond-to-diamond bonding.

The wire-drawing dies made with these lumps have worked out quite well because they don't burst easily and they wear uniformly and slowly: 100,000 miles of copper wire is not unusual for such a die before it needs retouching. The tools are excellent for cutting hard abrasive materials like ceramics, rock, fiber-reinforced materials, and certain alloys like the silicon-aluminum used for automotive engine pistons. But don't try them on steel or nickel-based alloys. Here once more chemistry rears its beautiful head; these metals when hot have a devastating effect on diamond.

Luckily nature has provided us with some small atoms on either side of carbon, namely boron and nitrogen, and boron nitride, BN, bears many resemblances to carbon. Like graphite, it can exist as a soft, slippery solid. And at high pressures and temperatures like those used for synthesizing diamond from graphite, the soft BN can be transformed into a hard, diamond-like cubic form. The catalysts for this transformation are not iron, nickel, and the like; instead the best catalysts are found to be nitrides, particularly the salt-like nitrides such as those of lithium or magnesium.

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Cubic BN has almost as much bonding energy per cubic cm as diamond, and so it is almost as hard. Figure 4-8 shows the structure of Cubic BN, and Figure 4-9 shows some crystals of it. Cubic BN is more inert than diamond toward attack by oxygen or hot iron or nickel, and therefore has found wide use as an abrasive for hard steels and nickel-based alloys. A cubic boron nitride abrasive wheel wears very slowly and is extremely useful where close tolerances must be maintained on the workpiece, as in tools with many teeth such as broaches or milling cutters, or where many parts must be made to exact sizes, such as bearings.

Cubic BN grains may also be bonded and sintered together into hard, strong masses which make excellent cutting tools for hard steels and nickel-based alloys, and chilled cast iron. Figure 4-10 shows such a tool, and Figure 4-11 shows one peeling off a red-hot chip from a piece of jet-engine alloy. Here the tool is so strong and refractory that it can be operated at temperatures above those at which the workpiece material softens.

So we see that diamond and cubic BN form a complementary pair, with one taking up where the other leaves off. As far as we can tell, they don't seem to be soluble in each other to any great extent. Neither does something harder than diamond seem to be available from such a combination.

Sometimes people ask us why, with all this high-pressure equipment, we don't make something harder than diamond. We always reply that we would be glad to, but what should we make it out of? It is difficult to improve on carbon, with its small effective atomic radius and four strong chemical bonds per atom. We really need some more elements in the first row of the periodic table, and as you all know, making new elements is not easy, even for a physicist.

We hope that you have enjoyed our talk on just the three elements that have been so interesting to us: boron, nitrogen, and carbon. Thank you.

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Fig 4-1

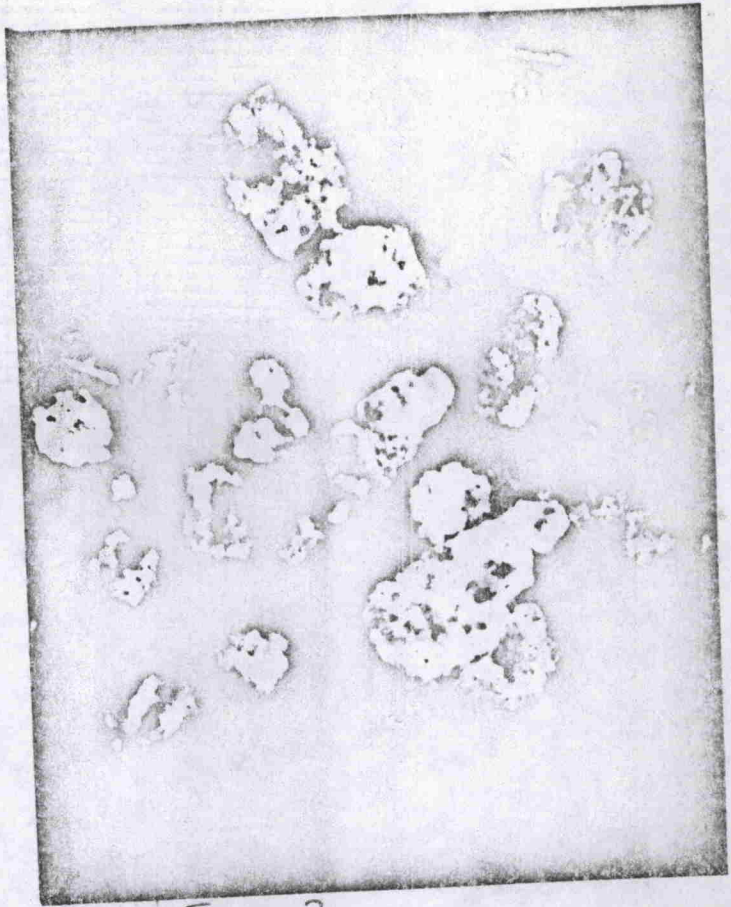
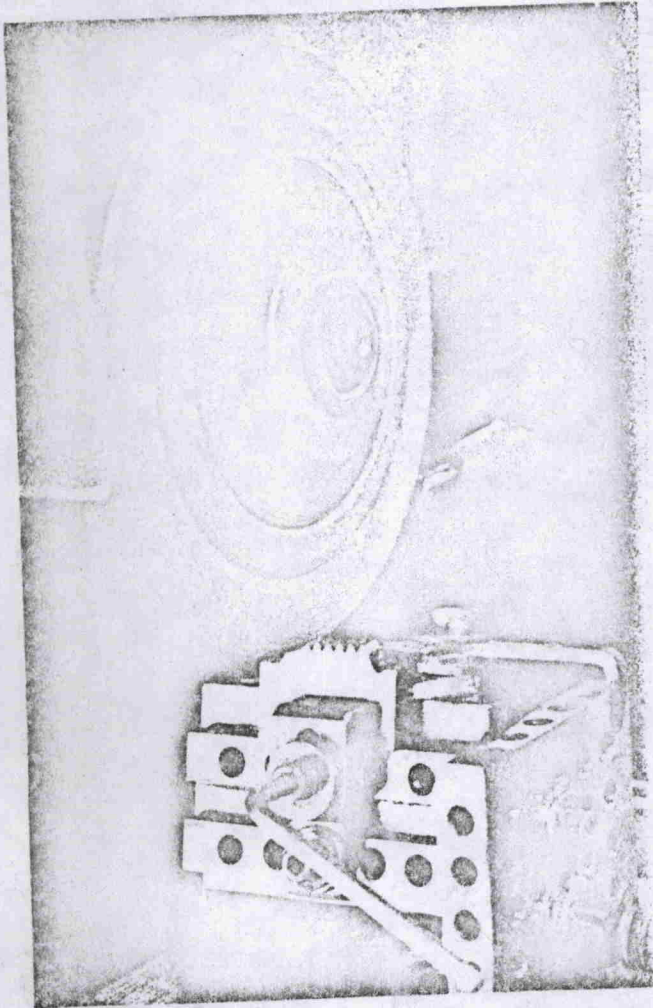


Fig. 2

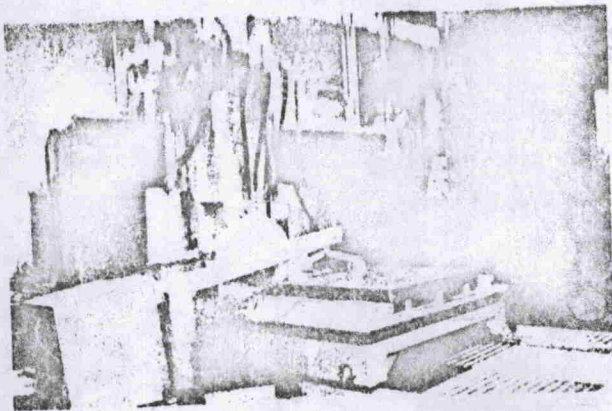


Figure 3 Automated Cut Off Machine

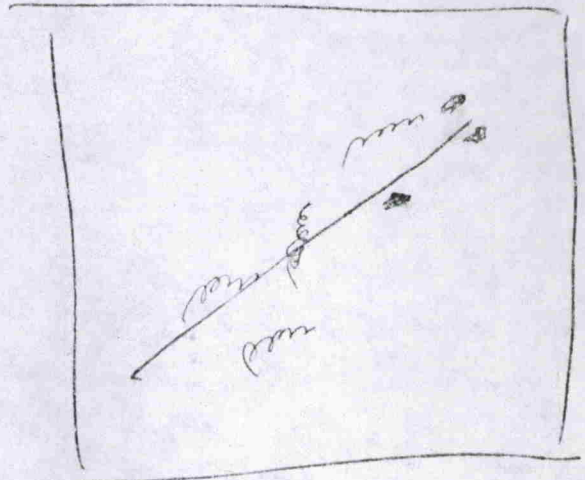


Fig 4

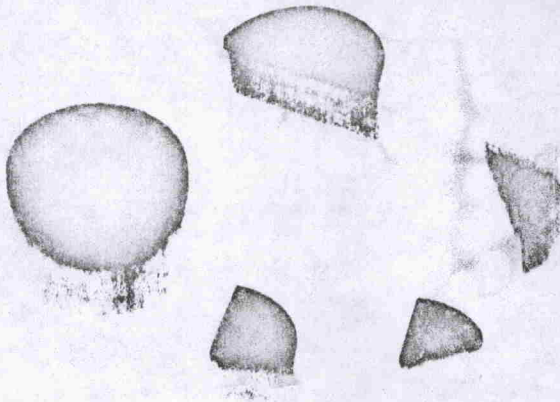
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Fig. 5

Fig 6-A

COMPAX diamond tool blanks



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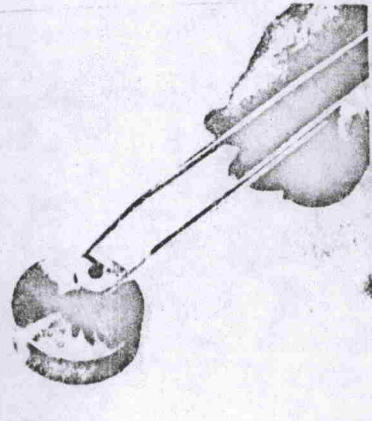
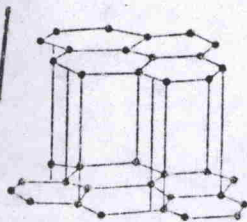


Fig. 6-B

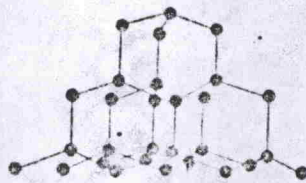
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Figure 7. Diamond compact, sintered for (a) 5 min, (b) 60 min (x 200).

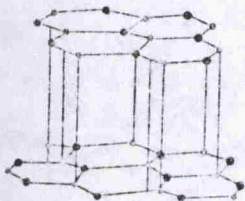


GRAPHITE

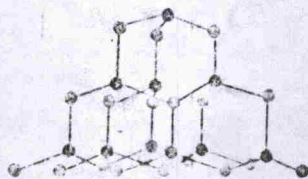


DIAMOND

- CARBON
- BORON
- NITROGEN



BORON NITRIDE



BORON NITRIDE "DIAMOND"

FIG. 8





Fig. 9

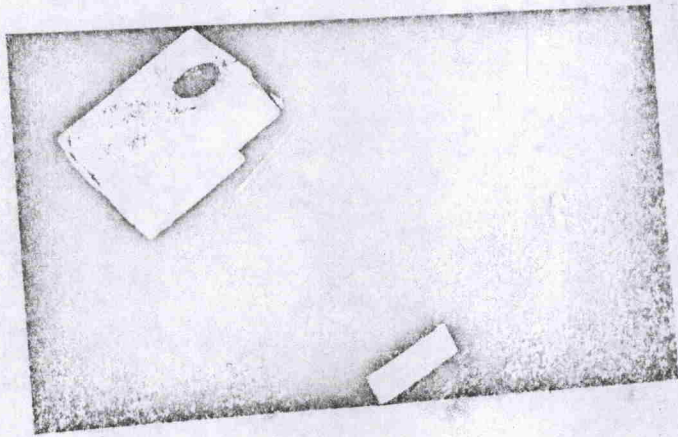


Figure 6. Finished Borazon compact and toolholder.

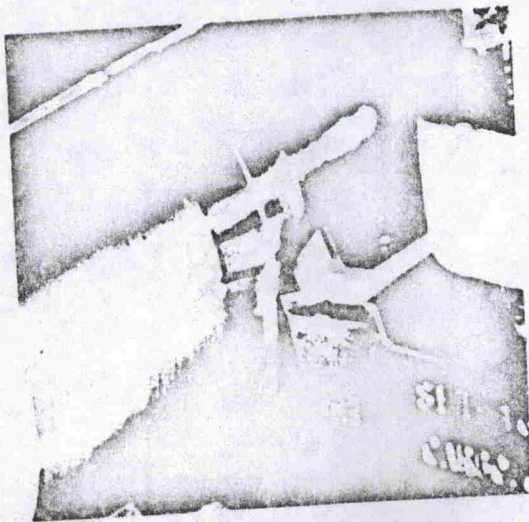


Figure 7. Machining Inconel 718 with a CBN compact at  $4 \text{ m s}^{-1}$ .

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