JTTEE5 10:249-254



# Turning of Thick Thermal Spray Coatings

**L.N. López de Lacalle, A. Gutiérrez, A. Lamikiz, M.H. Fernandes, and J.A. Sánchez**

(Submitted 14 March 2000; in revised form 13 June 2000)

**This technical note looks at several attempts to machine parts coated with Ni5Al thermal spray. This coating is used in the overhaul and repair of gas turbine components. Machining the thermal sprays to achieve the dimensional tolerances and surface finish is needed. Turning tests were performed with small carbide inserts and with CBN. A study was made of tool performance and cutting process. In this way, tool life, wear mechanism, chip formation process, and actual roughness of turned parts were analyzed. In addition to the good performance of CBN inserts, some disadvantages of using coolant with CBN tools were detected and analyzed.**

**Keywords** CBN, coatings, machining, nickel alloys, turning

## 1. Introduction

Thermal spray coatings are a response to the requirements of various industries. One of these requirements is the need to repair workpieces whose dimensions have altered because of wear or accident, or because, following errors in manufacture, tolerances were exceeded. The present note looks in particular at Metco 450 thermal spray. Made from $Ni_5Al$ powder (4.5% aluminum, balance nickel), this spray is used mainly in parts recovery. It resists oxidation well, while scattered hard particles of $Al_2O_3$[1] protect it against abrasion. It adheres well to such metals as aluminum, steel, and nickel alloys, materials most commonly used in gas turbines. The characteristic properties of this coating are macrohardness 65 to 70 $HR_b$, density of about 7.2 to 7.4 g/cc, texture as sprayed approximate to 500 to 600 $\mu$m, porosity less than 0.5%, and bond strength on ground substrates of low carbon steels greater than 21 MPa. But it is one of the most difficult coatings to machine. A solution for cost-effective machining of this coating could be extended[9] to other, more easily machined contributions, such as Metco 447, 45 C, and 443.

Figure 1 shows the structure of Metco 450 before machining. Each coating layer, the result of a gun application, is about 0.02 mm thick and irregularly shaped. Surface oxidation occurs in the period required for the gun to go over the same point again. This oxidation delimits different coated layers, which exhibit dark points. A point with a regular shape is the result of hard inclusions. Points that are irregular, as well as grouped or interconnected, are pores. Where adherence to the substratum is concerned, the thermal spray coating generally depends on the mechanical bond between surfaces.[2] In other words, the spray adapts its shape to the bumpy texture and surface roughness of the workpiece. However, if on the surface there are impurities, such as oxides or traces of grease, the result may be poor coating to substrate bond in Fig. 1(b). Preparation usually entails the removal of grease and an aggressive surface roughening process (blasting, rough threading, or knurling) that will make the surface rougher and facilitate mechanical bond.[5] The strength of the mechanical bond between the $Ni_5Al$ and the sprayed surface must be at least 20 MPa according to tensile test.[6] To achieve strength of 40 MPa is rather difficult.

The reference value for machining is the maximum shear stress. In the case of Metco 450, it is at least 80 MPa.[6] Microhardness at the cross section of the contribution will probably be about 80 HRb (150 Brinell), although one should note the high dispersion resulting from the heterogeneity of the material at this scale.

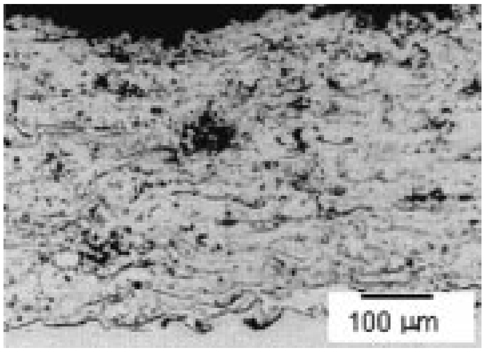
### 1.1 Machining of the Coated Film

Spray deposit results in granulated surfaces, and dimensional control is poor. Hence, it is nearly always necessary to machine the deposits in a finishing operation,[3,4] so that one may achieve the tight geometric, dimensional, and roughness tolerances required. In practice, machining will give rise to two basic problems. On the one hand, adherence to the base substratum is relatively limited, while on the other, carbide tool cutting edges wear quickly even at speeds as low as 30 m/min. The situation becomes more serious when the workpiece exhibits large cutting discontinuities, since the coating borders exhibit a lower adherence. For example, it is common to find little flakes of sprayed material around the holes in the supporting flanges of turbine casings recovered *via* thermal spray. The result is an unbalanced tightening force when the frames are reassembled.[7]

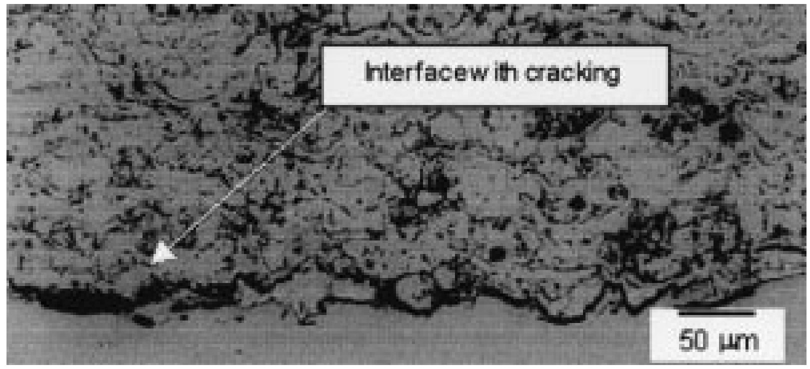
There are several reasons for the rapid deterioration of cutting edges. Chief among them is the hard abrasive particles, *i.e.,* oxides and carbides that result from spraying in the open atmosphere. Material porosity may also be to blame. It can easily be shown that, in the case of synthesized materials, the wear rate proportional to the porosity level[8] may be involved. In most workshops, machining is at 30 to 40 m/min, with tungsten carbide inserts with a 6% Co binder. Feeds and cutting depths are kept down, the aim being not only to minimize cutting forces, and hence avoid coat spalling, but also to ensure a good finish.

The enhancement of tool materials used in cutting hard alloys has led to studies suggesting their potential, especially where polycrystalline cubic boron nitride (PCBN) is concerned, for precision machining and for machining in factories. Reference might, in particular, be made to the work done by General Electric Abrasives.[7,9]

**L.N. López de Lacalle, A. Lamikiz, and M.H. Fernandes,** Department of Mechanical Engineering, University of the Basque Country, 48013 Bilbao. **A. Gutiérrez and J.A. Sánchez,** Industria de Turbopropulsores S.A., Zamudio. Contact e-mail: implomal@bi.ehu.es.




(a)




(b)

**Fig. 1** (**a**) and (**b**) Micrographs of the Metco 450 used, at 100 and 200×

## 2. Work Plan and Tests

The study was developed in two stages, which are described below. The present article offers some conclusions, relating to such matters as tool performance and surface quality. Previous to this study, some reference tests using carbide tools were carried out with cutting speeds and feeds commonly used in the $Ni_5Al$ coating machining, that is, cutting speed of 30 m/min and feed 0.05 to 0.12 mm/rev.

**Initial Study.** We must check whether the PCBN grades, optimized for the machining of heat resistant superalloys (Ni-Cr-Co-Fe-Mo-W), which are characterized by having a higher CBN content than when dealing with the finishing of hardened/quenched steel, and with Co binders rather than ceramic ones, are also adequate for a productive machining of coatings. This is important because the overhaul of jet-engine parts frequently involves both the cutting of the coating and the substrate, and the latter is a superalloy. Therefore, it would be desirable for the used insert and the cutting conditions to be compatible. We look at most general aspects of the machining process, which up to now have not been studied in depth.

**Optimization.** In the interest of productivity, the first aim is to determine how great the feeds, depths of cut, cutting speeds, and wear can be at maintaining coating integrity. On the other hand, we would like to relate these parameters to the thermal and mechanical loads, which cause the catastrophic failure (spalling) of the spray coating. On the other hand, the price per cutting edge is high, ranging from 30 to 60 € depending on make. The use of PCBN is accordingly limited.

Our test material comprised several cylinders made of AISI 1018 low-carbon steel. To these, a Metco coating of 1.7 to 1.8 mm was applied with the Multicoat Atmospheric Plasma Spray (Sulzer-Metco, Wohlen, Switzerland) equipment. The cylinders, 250 mm long and 100 mm in diameter, were sprayed up to about 200 mm. Some of these cylinders exhibited four canals with a square section of side 10 mm, at 90°, to effect cutting discontinuity.

To maximize stiffness, turning was carried out between clutches and point, with an 11 kW lathe, both dry and with a coolant (synthetic emulsion CIMTECH 400, MSL 10%). The tests programmed are shown in Tables 1 and 2. In these, $V_c$ is the surface cutting speed, $f$ is the feed per revolution, and $a_p$ is the radial depth of cut. Flank wear in both the primary and secondary faces was measured using an optical microscope. Average roughness ($R_a$) was de-

**Table 1 Programming of continuous turning tests**

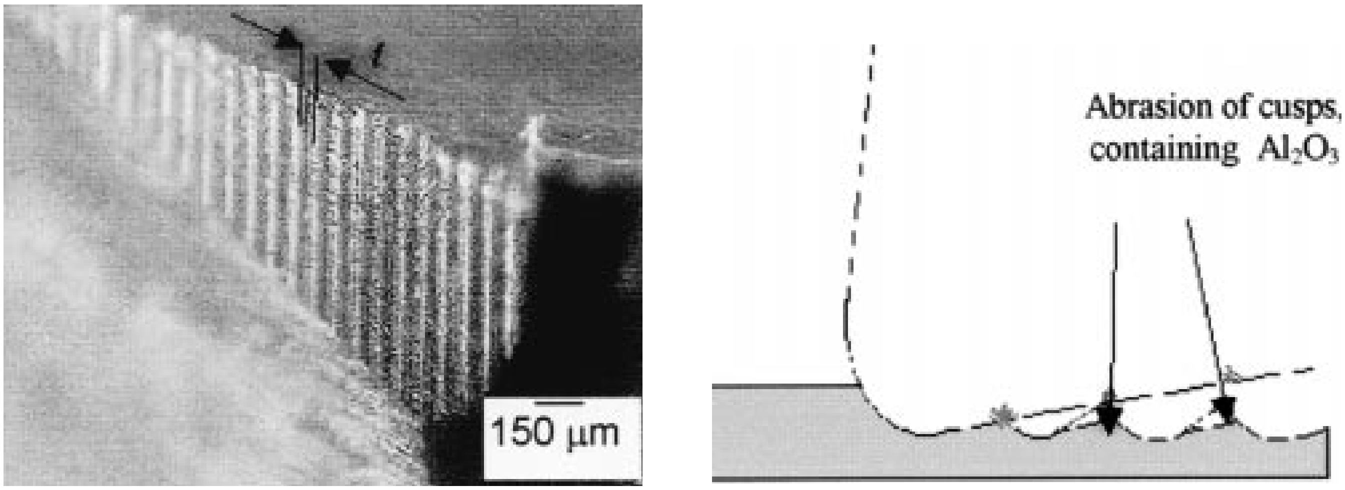
| Test number | $V_c$ (m/min) | $f$ (mm/rev) | $a_p$ (mm) | Insert |
|---|---|---|---|---|
| Test-1 | 30 | 0.05 | 0.05 | (1) |
| Test-2 | 30 | 0.05 | 0.12 | (1) |
| Test-3 | 30 | 0.12 | 0.12 | (1) |
| Test-4 | 30 | 0.12 | 0.12 | (2) |
| Test-5(a) | 30 | 0.12 | 0.12 | (2) |
| Test-6(a) | 30 | 0.12 | 0.12 | (1) |
| Test-7 | 30 | 0.05 | 0.05 | (3) |
| Test-8 | 90 | 0.05 | 0.05 | (3) |
| Test-9 | 135 | 0.05 | 0.05 | (3) |
| Test-10 | 180 | 0.05 | 0.05 | (3) |
| Test-11 | 30 | 0.12 | 0.12 | (3) |
| Test-12 | 90 | 0.12 | 0.12 | (3) |
| Test-13 | 135 | 0.12 | 0.12 | (3) |
| Test-14 | 180 | 0.12 | 0.12 | (3) |
| Test-15(a) | 90 | 0.05 | 0.05 | (3) |
| Test-16(a) | 180 | 0.12 | 0.12 | (3) |
| Test-25 | 180 | 0.05 | 0.12 | (3) |
| Test-26 | 220 | 0.12 | 0.12 | (3) |
| Test-27 | 180 | 0.12 | 0.05 | (3) |
| Test-28 | 180 | 0.20 | 0.05 | (3) |
| Test-29 | 260 | 0.12 | 0.05 | (3) |

(a) Tests with coolant:
(1) Carbide tool (K10) CCGX 120404-AL (Sandvik H10A)
(2) Carbide tool (K10) CNGP 120412-QM (Sandvik H10A)
(3) PCBN CNMA 120408-T (Mitsubishi MB730)

**Table 2 Programming of discontinuous and dry turning**

| Test number | $V_c$ (m/min) | $f$ (mm/rev) | $a_p$ (mm) | Insert |
|---|---|---|---|---|
| Test-101 | 75 | 0.15 | 0.15 | (1) |
| Test-102 | 75 | 0.15 | 0.15 | (4) |
| Test-103 | 150 | 0.15 | 0.15 | (3) |
| Test-104 | 200 | 0.15 | 0.15 | (3) |
| Test-105 | 250 | 0.15 | 0.15 | (3) |
| Test-106 | 300 | 0.15 | 0.15 | (3) |
| Test-107 | 150 | 0.15 | 0.15 | (3) |

(1) Carbide tool (K10) CCGX 120404-AL (Sandvik H10A, Sandviken, Sweden)
(2) Carbide tool (K10) CNGP 120412-QM (Sandvik H10A, Sandviken, Sweden)
(3) PCBN CNMA 120408-T (Mitsubishi MB730, Ibaraki, Japan)
(4) Carbide tool (K10) CNMG 120404-QM (Sandvik H10A, Sandviken, Sweden)




(a) (b)

**Fig. 2** Wear trace in the secondary flank of a K10 insert. (**a**) Abrasion is apparent and (**b**) wear mechanism

termined with a roughness measurement device with a view to characterizing the surfaces in regard to the usual design requirements, while average maximum roughness ($R_z$) was determined for comparison with the magnitudes theoretically estimated.

The choice of the carbide—grade K10—inserts with an extremely positive geometry is related to the coating features. It is abrasive, but with a low specific cutting energy. We used two inserts with CNMG geometry in order to assess the influence on geometry of an insert more commonly used in cutting tough materials. For the cutting at high speeds CBN MB730 (Mitsubishi Industries, Ibaraki, Japan) was selected.

The tests were set up not to exceed a wear rate of 0.3 on the main flank, since, beyond that point, overpressure and cutting forces may damage the thermal spray coating. All tests were carried out twice in order to have a reasonable statistical reliability.

## 3. Results

### *3.1 Cutting Edge Wear*

While every case has its peculiarities, carbide and CBN inserts have a common feature. Wear was always observed to appear on the secondary flank (Fig. 2a), spreading toward the point radius. It was never noticed on the primary cutting edge or at the rake face. This phenomenon usually occurs where superfinishing has been carried out with low cutting depths,[10] but never in such intensity.

In Fig. 2(a), a trace of bright wear in the carbide can be observed. Neither adherence, cracks, nor plastic deformation is readily apparent. There does appear to be, however, a series of regularly spaced grooves or lines, these resulting from the abrasive action of the cusps of material from the surface already machined (Fig. 2b). It was in fact shown that the distance between these grooves is in every case equal to the feed used (0.05 or 0.12 mm). As was to be expected, these canal-like lines are not found with CBN tools since in this case the tool material is much harder.

Figure 3 reflects the secondary wear of carbide and CBN tools at different cutting speeds. The principal conclusion, as may be evident, is that the investment in advanced materials for this particular application would be cost-effective. In certain tests, performed with real parts, a carbide insert (at 30 m/min) was needed, in order to turn a part that involved the removal of 12 $cm^3$. The wear was near the admissible 0.2 mm. With a CBN edge (at 200 m/min), it was possible to machine as many as 12 workpieces before loss of surface quality. When the wear reached 0.16 mm, it was advisable to replace the CBN insert.

Figure 4 depicts the results with CBN inserts at a constant speed of 180 m/mm and under various conditions. Here, it is yet more apparent that wear is virtually independent of feed (0.05 to 0.20 mm/rev) and depth (0.05 to 0.12 mm) at a fixed cutting speed. Coolant (Test-16) could be clearly seen to exacerbate wear. Because the appearance of wear in Test-16 was different from that observed in other cases, both under the stereoscopic microscope and under the measurement microscope, we decided to examine it qualitatively. The methods we used were observation with a scanning electron microscope (SEM) and energy-dispersive x-ray analysis. Figure 5 shows how, at the very center of the area being abraded, there is an irregular, alveolar patch, which could have been caused by chemical attack of some type. To investigate this hypothesis, we measured the x-ray spectrum at the center of the patch and at a point on the main flank that showed no sign of wear. Both spectra are displayed in Fig. 6. In Fig. 6(b), we see peaks corresponding to the ions dissolved in the water ($Na+$, $Mg^{2+}$, and $Ca^{2+}$) that is the emulsifying base for the coolant.

The most commonly observed reaction of CBN in water is to transform into boric acid and ammonium. The chemistry of these solutions is quite complex, but basically the boric acid may in turn give rise to salts of the metals usually dissolved in running water, such as sodium, calcium, and manganese. This reaction is significant only beyond ranges from 700 to 800°C Thus, there are grounds for believing that these elements are incorporated into the insert areas in which the boric acid is produced. Two immediate heat sources can play a major role in order to increase the temperatures to the level suggested by CBN dissociation. The first is the presence of uncut coating stocks subject to the

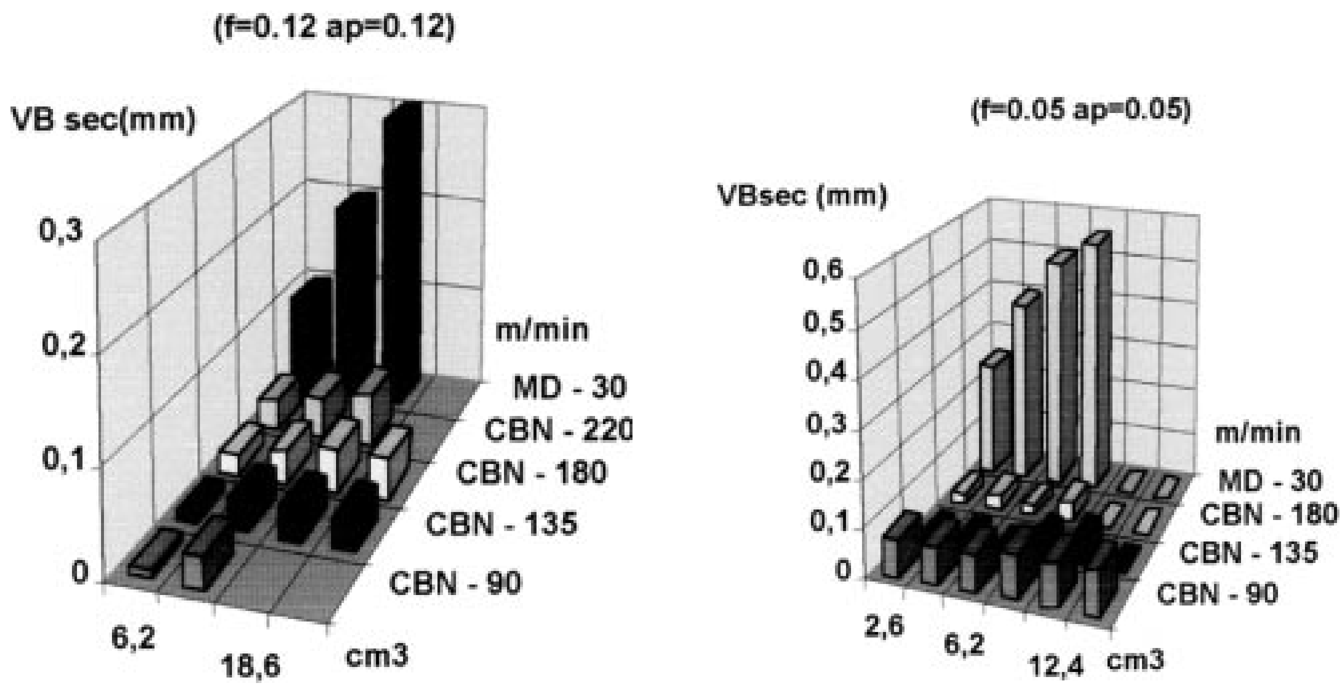



**Fig 3** Cutting performance with different tool materials and at various cutting parameters

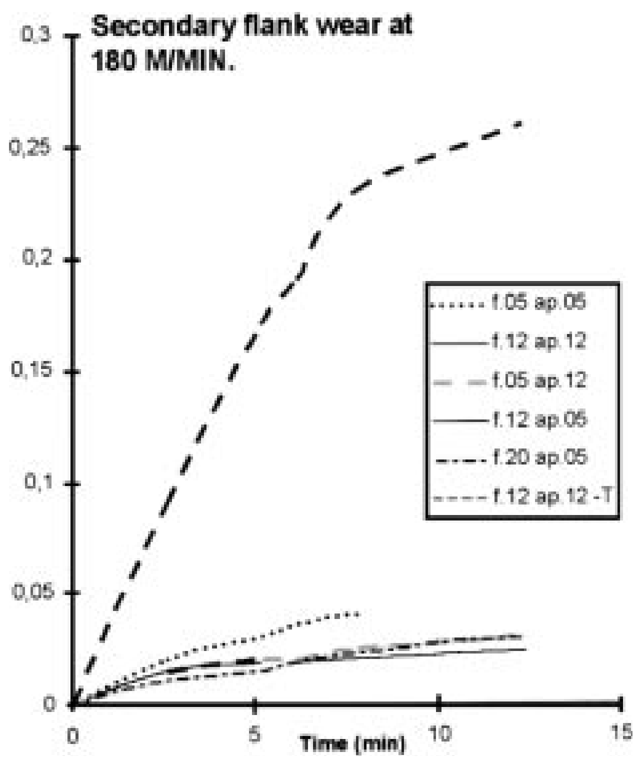



**Fig. 4** Wear in CBN inserts at 180 m/min

highly compressive pressures along the normal direction to the layered structure, probably the only way to obtain meaningful plastic strains. It is well known that the high specific energy implied by the abrasive action due to the size effect causes severe thermal loads both on the workpiece and tool. The second are the abrasive cusps of the machined surface containing $Al_2O_3$; these

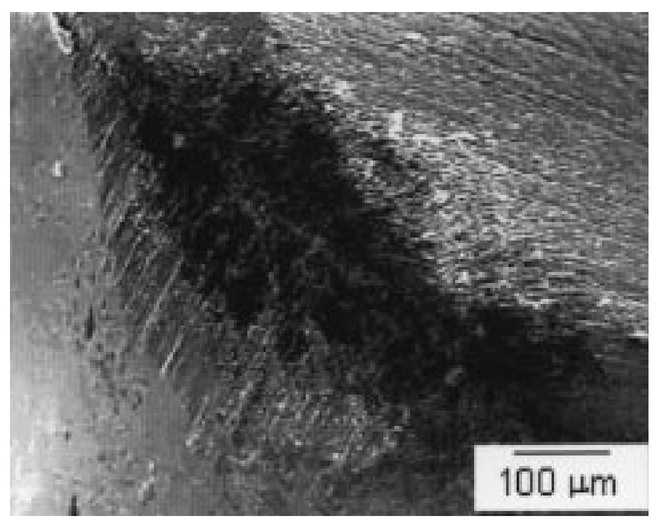


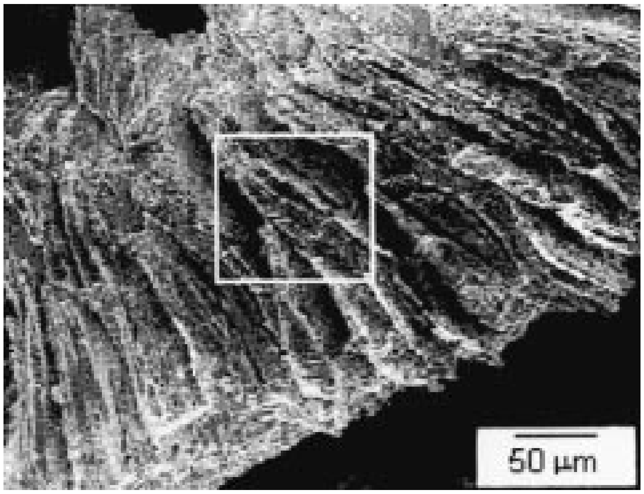

**Fig. 5** Wear pattern in the secondary flank. The appearance of the central area is irregular

are supposed to tear away material coming from the secondary flank of the insert.

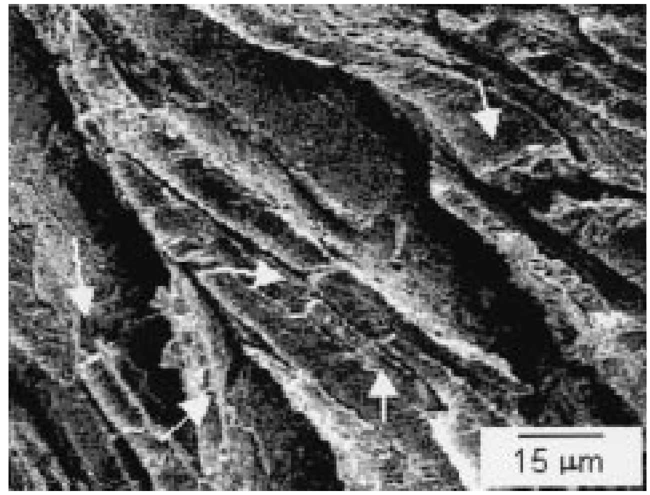
The influence of chemical attack at a cutting speed of 135 m/min is also observable, but the size of the wear area is half that shown in Fig. 5. At lower speeds, it has not been possible to detect this effect.

### *3.2 Chip and Surface Formation*

Figure 6 shows the SEM image of a chip that has been generated in a fragmented manner. The extreme fragmentation was to be expected in view of the numerous defects, pores, and inclusions to be found in the coating. Undoubtedly, they would




**(a)**




**(b)**

**Fig. 6** Electron microscope images at (**a**) 750× and (**b**) 2000×

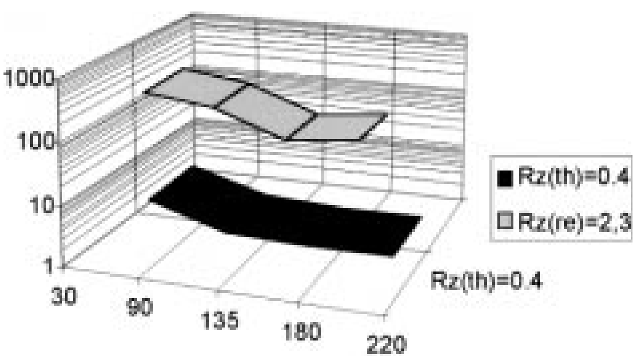



**Fig 7** Relation between theoretical and real roughness, at different cutting speeds

serve as tension concentrators, and as discontinuities, in a manner similar to that observed in gray iron castings. Such a finding is consistent with the near-absence of wear in the main flank. Small crossed cracks can be observed in every layer (Fig. 6b), which results from the fact that there is almost no capacity for absorbing the plastic deformation deriving from small lateral stresses, which tend to widen the chip slightly in response to triaxial cutting stress.

### 3.3 Tolerances and Roughness

In tests Test-1 to Test-6, a tapering effect from 0.1 to 0.25 mm was observed as wear progressed. This is because secondary face wear has direct influence over the geometry of tool (Fig. 2). In this manner, as wear increases, the radial depth of cut decreases. On the other hand, CBN inserts do not seem to be responsible for any conicity in the external turning of the cylinders within a precision of 0.01 mm, because secondary wear does not appear, or it only appears in a small amount.

Where maximum roughness levels ($R_z$) are concerned, there were two principal findings. First, they are much higher than the minimum predicted by theory. Second, the wear range exhibits certain stability. In each case, the reason is the porosity of the sprayed coating, along with the variations that this porosity may exhibit between one workpiece and another.

Two main tendencies can be deduced.

(1) The ratio $\eta$ = (real $R_z$)/(theoretical $R_z$) diminishes (Fig. 7) with speed up to about 200 m/min, at which point it becomes stable or increases slightly.

In particular, in the case of tests with a theoretical $R_z$ of 0.4, i.e., tests Test-7 and Test-10, the following relationships between the roughness ration ($\eta$) and cutting speed are found: $V_c = 30$ for $\eta = 112.5$, $V_c = 90$ for $\eta = 75$, $V_c = 135$ for $\eta =$ 28.75 to 23.75, and $V_c = 180$ for $\eta = 38.5$ to 28.

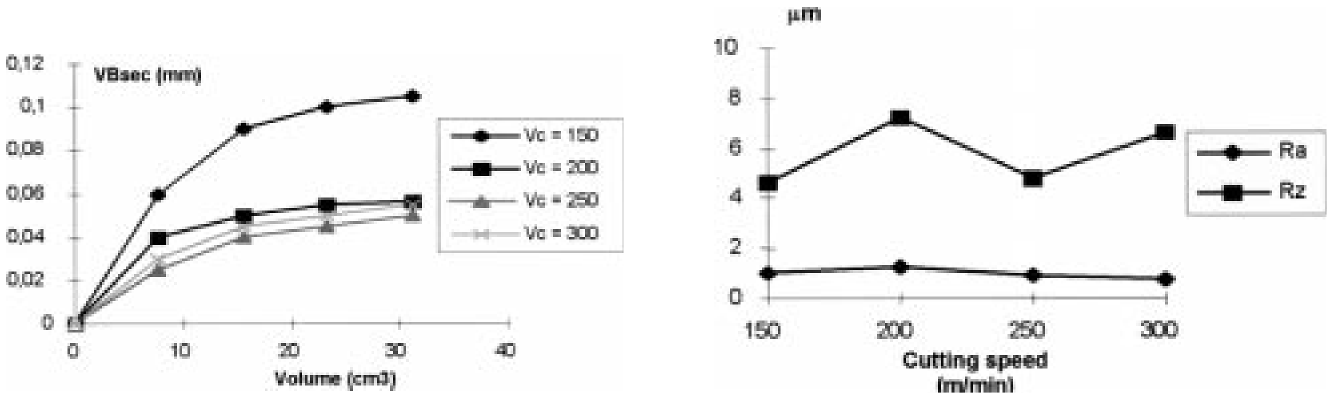
| $V_c = 30$ | $V_c = 90$ | $V_c = 135$ | $V_c = 180$ |
|---|---|---|---|
| $\eta = 112.5$ | $\eta = 75$ | $\eta = 28.75$ to 23.75 | $\eta = 38.5$ to 28 |

In the case of tests with a theoretical $R_z$ of 2.3, *i.e.*, Test-12, Test-13, Test-14, and Test-26, $V_c = 90$ for $\eta = 13.04$ to 8.7, $V_c = 135$ for $\eta = 5.78$ to 4.91, $V_c = 180$ for $\eta = 5.09$ to 1.43, and $V_c = 220$ for $\eta = 5.17$ to 4.13.

| $V_c = 90$ | $V_c = 135$ | $V_c = 180$ |
|---|---|---|
| $\eta = 13.04$ to 8.7 | $\eta = 5.78$ to 4.91 | $\eta = 5.09$ to 1.43 |
| $V_c = 220$ | | |
| $\eta = 5.17$ to 4.13 | | |

For the same reason, CBN tests are very much superior in finish to tests carried out with carbide tools, since, at the same speed, *i.e.,* 30 m/min, and under the same advance and depth conditions, CBN was seen to tear the surface.

(2) Similarly, the above values increase significantly when feed declines from 0.12 to 0.05. This finding would seem to be contradictory, since, in theory, $R_t$ is proportional to square feed $f^2$. The only reason that might be postulated is the presence of a minimum nondeformed chip thickness. Hence, the material left behind by the tool radius suffers a flattening effect produced by the secondary flank (*lateral plastic flux*); consequently, the roughness exceeds theoretical level. The less the feed and the lower the speed, the greater the increase. Some studies performed on steel[12] have, in fact, shown the development of




**(a)** **(b)**

**Fig. 8** (**a**) and (**b**) Wear and roughness in dry interrupted cutting tests with CBN tools

roughness in a sense direction similar to what we have shown here, but there is an essential difference. This phenomenon is based on the deformation capacity of the steel in a relatively cold area,[11] whereas the ductility of Metco 450 is only slight.

### *3.4 Summary Regarding Discontinuous Cutting Tests*

In general, there was no change in the wear pattern or wear rate exhibited by the insert, because the wear mechanism is not influenced by the shock experienced by the tool (Fig. 8). There is one exception, however, specifically with the test at 150 m/min. Here, there were problems determining a uniform roughness. In this test, the chip exhibited an interesting variation. Morphology was arborescent, just as if the cutting edge had torn up the coating material (effect named "chip foot"), instead of cutting the material. This effect produces an irregular surface, with little spots. This phenomenon is common to other nickel alloys. Also observed was an increase in chip length with speed, although always of fragmented appearance.

## 4. Conclusions

Internal cohesion of the coating was seen to be inferior to that of conventional materials. In view of the laminar structure and of discontinuities, in the form of pores and hard particles, most of our observations are directly explained as follows:

- lack of plastic deformation mechanisms in cutting processes (the cutting process is a sequence of microcracks);
- abrasive wear on the secondary flank, owing to constant friction with the machined surface; and
- because there was no secondary shear, weakness in the primary shear and a small chip section (this is a common feature of nonductile materials).

Some of our data suggest a minimum thickness for the nondeformed chip, the cutting of which necessarily produces intense friction. This would explain the grooves in the secondary flank. Without too much material remaining, it would give rise to, at most, two grooves.

The principal conclusion, as may be evident, is that the investment in advanced materials for this particular application would be cost-effective.

The use of a coolant seems to be unadvisable, except in those cases in which it is necessary to improve surface quality.

Wear starts at the secondary flank and progresses toward the insert radius. Hence, whenever carbide tools are used, wear itself will be apparent before it begins to interfere with coating integrity.

Cutting parameters, in general, should be the largest that the coating can withstand without spalling. If tests cannot be performed, $V_c$ 200 to 250 m/min and $f$0.1 mm/rev may be enough to make CBN cost-effective.

It is recommended that cutting inserts with sharp edges, and positive rake and flank angles, be used in view of the limited strength and toughness of the coating. Exceptions are those cases in which it is necessary to simultaneously cut both the coating film and the base material.

### References


1. H.S. Ingham and A.P. Shepard: *Flame Spray Handbook,* Plasma Flame Processing, Metco Inc., New York, NY, 1965, vol. III.
2. S. Safai and H. Herman: *Treatise on Materials Science and Technology,* VCH, New York, NY, 1986, vol. 20.
3. J.H. Clare and D.E. Crawmer: *Metals Handbook,* vol. 5, *Finishing, Cleaning and Coatings,* ASM International, Materials Park, OH, 1989.
4. *Thermal Spray Coatings: Properties, Processes and Applications,* T.F. Bernecki, ed., ASM International, Materials Park, OH, 1991.
5. J. Wigren: in *1994 Thermal Spray Industrial Applications,* C. C. Berndt and S. Sampath, eds., ASM International, Materials Park, OH, 1994.
6. *Technical Bulletin of Metco 450 Nickel Aluminum Composite Powder,* Sulzer-Metco, Wohlen, Switzerland, 1983.
7. J.H. Dailey: *American Machinist,* Nov. 1996.
8. H.E. Chandler: *Metals Handbook, vol. 16, Machining,* ASM International, Materials Park, OH, 1989.
9. J.H. Cohen and J.H. Dailey: ASME Technical Paper 94-GT-399, *Gas Turbine and Aeroengine Congr. Exp.,* La Haya, The Netherlands, June 1994.
10. M.C. Shaw: *Metal Cutting Principles,* Clarendon Press, Oxford, United Kingdom, 1983.
11. A.P. Sokolowksi: *Präzision in der MetallbearbeitungPrecision in Metal Working,* VEB Verlag Technik, Berlín, 1955 (in German).
12. T. Sata: *Ann. CIRP,* 1964, vol. 12, p. 190.