How to machine compacted graphite iron

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CGI has a tensile strength at least 75% greater than gray iron and a roughly double fatigue strength, so less material is needed in automobile engines. But machining is a challenge

Few materials have generated the enthusiasm of compacted graphite iron (CGI) in recent years. Commercially available for many years and superior to gray iron in mechanical performance, the absence of reliable foundry production had precluded extensive use. With the advent of process control, however, quality castings have become rather routine, spurring high-volume production applications, notably in auto engines.

This in turn has prompted extensive efforts to optimize machining for converting castings into precision products. Carbides at low to moderate cutting speeds seem to be recommended by most insert manufacturers. But one company has achieved excellent results with silicon nitride (Si_3N_4), and at far greater speeds.

Why the interest in CGI

Although graphite accounts for less than 4% by weight of cast iron, the shape of these particles determines physical and mechanical properties. In compacted graphite iron (CGI), the graphite appears as vermicular, or worm-like, particles and, three-dimensionally, as an entangled coral-like network in which graphite continuity provides good thermal conductivity and vibration damping. Moreover, the rounded edges and rough surfaces of the particles improve adhesion with the iron matrix, increasing, relative to gray iron, tensile strength at least 75% and stiffness 35% while roughly doubling fatigue strength, as shown in the table.

The change of graphite shape from flake-like in gray iron to compacted in CGI and spheroidal in nodular, or ductile, iron is a function of the amount of magnesium modification. This transition can be represented by the so-called magnesium S curve, which indicates a stable CGI plateau between the production ranges for gray and nodular irons. Stable CGI production exists only within a range of about ±0.003% magnesium from a target point that must be uniquely defined for each casting. Depending on melt chemistry, fade time and solidification rate, the size and even the location of the actual plateau can move entirely out of the intended production range.

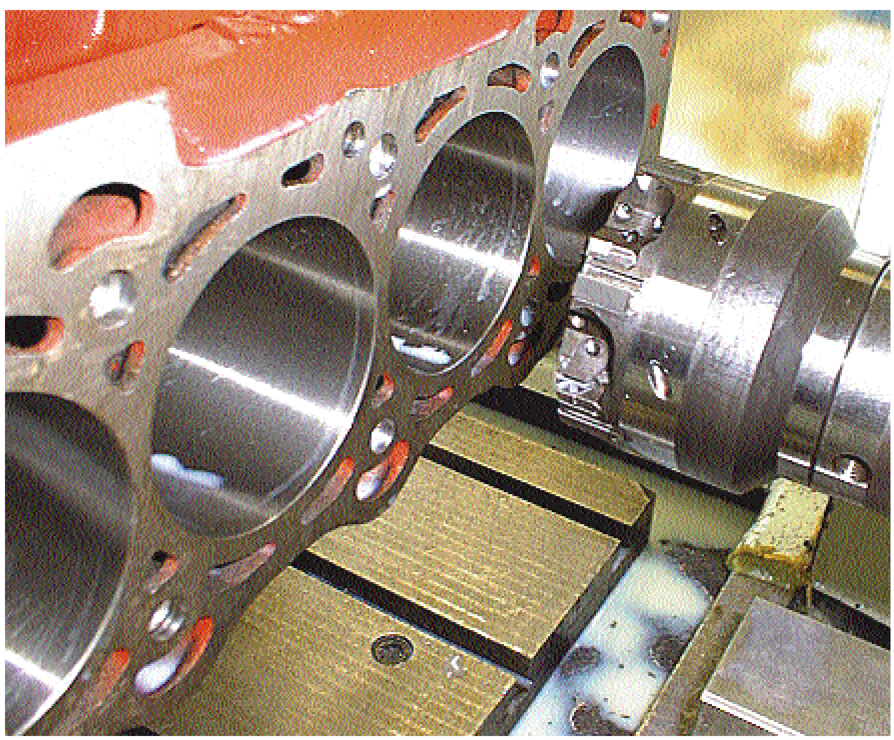

Fig 1. Machining cylinder bores in CGI engine block using fixed multiple carbide inserts on rotary tool *(Mapal)*

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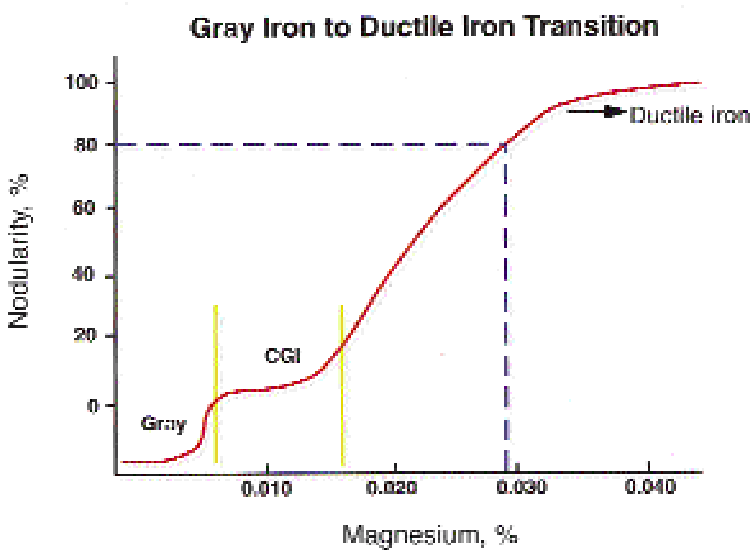


Gray iron to ductile iron transition. CGI lies within narrow range of magnesium content *(SinterCast)*

***CGI bridges the gap between gray and nodular irons*[a]**

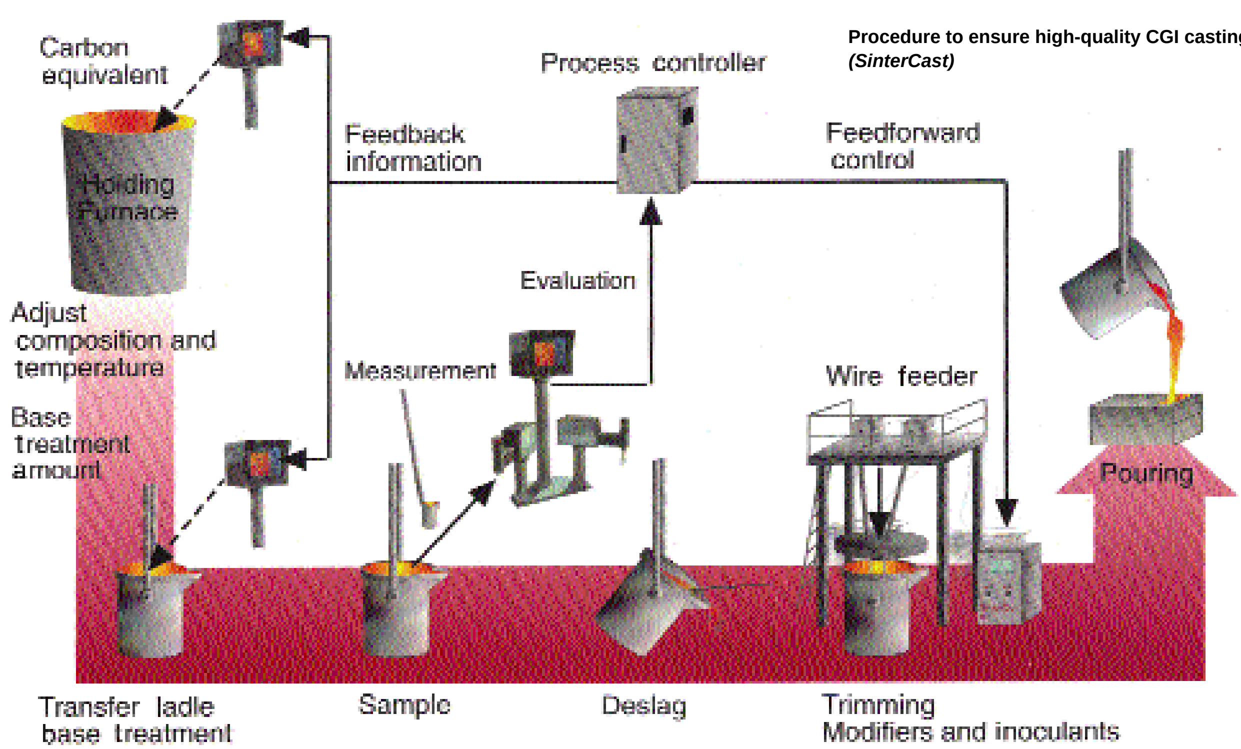
	Gray iron	CGI			Nodular iron
Matrix	Pearlitic	Ferritic	Pearlitic	Ferritic	Pearlitic
Tensile strength, MPa	200-270	330-410	420-580	400-600	600-700
Yield strength (0.2%), MPa	115-210	240-305	345-415	285-315	375-482
Modulus, GPa	105-115	130-150	130-155	155-165	160-170
Fatigue strength, MPa	95-110	155-185	190-225	185-210	245-290
Hardness, HB	175-230	130-190	200-250	140-200	240-300
Thermal cond, W/m.K	44-52	40-45	31-40	32-38	25-32

[a] From SinterCast.

SinterCast Ltd has quantified the overlapping roles of oxygen, sulfur, inoculation and modification. High-quality CGI exists within a narrow inoculation and modification window, not a fixed magnesium plateau. Unlike in gray and nodular iron production, high-quality CGI production cannot rely on overtreatment. The fundamental basis of the company's process is that the degree of inoculation and modification must be simultaneously controlled to stay within the CGI window. (SinterCast, of Stockholm, has its US office in Auburn Hills, Mich, with other offices in London, Sweden, Mexico, Germany and Tokyo.)

The superior mechanical performance of CGI over gray iron has led to major engine applications in the auto industry's quest for weight reduction. For its 2.5-liter V6 Calibra of the DTM race series, Opel AG cut engine-block weight 20.4% and weight-to-power ratio 70.7%. A prototype of its 1.6-liter Family 1 block was 29.4% lighter in weight. Audi's 3.3-liter V8 TDI (turbo direct injection) diesel and BMW's 3.9-liter V8d are both new designs in CGI, according to Steve Dawson, vice president and technology head, SinterCast (London). Choosing CGI rather than gray iron for the TDI reduced block weight 10%.

Besides nudging gray iron in engines, CGI may also stem the tide to aluminum for weight reduction. The iron, Dawson says, is about twice as strong and rigid, and has as

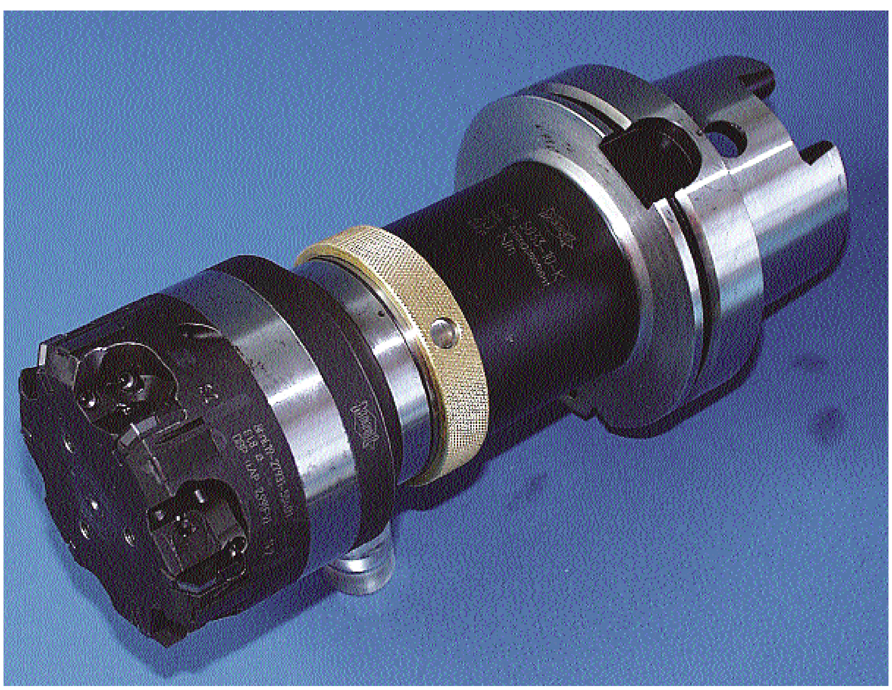


Procedure to ensure high-quality CGI castings *(SinterCast)*

Table 1. Cylinder boring pearlitic CGI with Si_3N_4 rotating-insert boring tool[a]		
Rough boring	V8 block	4-cyl, 2.0-l block
Bore dia, mm	70.5-72	78.9-80
Boring tool dia, mm	77.3	83.8
Depth of cut, mm	3.4	2.45
Spindle speed, rpm, m/min	3706, 900	2717, 713
Feed, mm/min	1667	1400
Feed, mm/tooth	0.45	0.52
Cutting time, sec	5.45	6
Results:	Bored 20 blocks, 160 holes. Wear land 130 µm. Heat generation a problem, lead insert had heat checks	Bored 15 blocks, 60 holes. Wear land 40 µm
Finish boring	4-cyl, 2.0-liter block	
Rough-bored dia 83.3 mm, Boring tool dia 84.7 mm, Depth of cut 0.45 mm		
Spindle speed, rpm, m/min	3000, 800	4000, 1065
Feed, mm/min, mm/tooth, and cutting time, sec	1905, 0.21, 4.40	2000, 0.166, 4.19
	2540, 0.28, 3.29	3810, 0.317, 2.20
	3810, 0.42, 2.20	4500, 0.375, 1.86
		5000, 0.417, 1.68
		5500, 0.458, 1.52
		6000, 0.197, 1.39

Results: Bored 15 blocks, 60 holes.
Wear land 10 micron. Greater feedrates reduced heat in block and tool. At 6000 mm/min, power consumption approached limit of machining center but was not a problem. Block, and boring tool after boring, were cold.

[a] From Rotary Technologies.
Data pertain to using three Si_3N_4 inserts.



much as five times greater fatigue strength at operational temperatures. Other applications for CGI include cylinder liners for diesel-engine blocks, which often can be cast to near net shape, and stationary and marine diesel engine frames, which have weighed as much as 17 tons. Also, more than 80,000 brake disks for high-speed trains have been made.

Boring engine blocks

Machining cylinder bores (Fig 1) is a critical operation in engine-block production and several tool manufacturers have developed or are developing rotary tools for this purpose. Using fixed multiple inserts are Ingersoll Cutting Tools (Rockford, Ill), Kennametal (Latrobe, Pa), Komet (Schaumburg, Ill) and Mapal (Piscataway, NJ). Rotary Technologies (Rancho Dominguez, Calif) is applying the rotating-insert concept.

The Mapal tool (Fig 2) has six inserts, four for semifinishing and two for finishing. C4 carbide was found to be the best cutting material, says Dr Berthold P. Erdel, president, better than ceramics and CBN. Tool guidance in the bore is secured, he says, with polycrystalline-diamond guide pads. Machining, however, should be done at comparatively low speeds and high feeds, he adds, such as 100 m/min and 400 mm/min. For a series of 67 nominally 80.840 x 130-mm (diameter x depth) bores, Fig 3 illustrates diameter variance, flank wear and surface finish.

In Rotary Technologies' system, three self-propelled round inserts are used in the roughing tool (Fig 4, next to last page) and two such inserts in the finishing tool. The bearing system within the rotary cartridge that supports the inserts provides continuous, vibration-free, self-induced rotation, permitting high chip loads and good surface finish, notes Harry M. Weiss, vice president. The cartridge's main component stator serves as a support and bearing element for thrust, radial and ball bearings. The rotor on which the inserts are mounted rotates freely during chip formation on the three types of bearings. High-temperature grease provides lubrication. The company has also developed a 152-mm-diameter rotating-insert face-milling tool, which uses eight inserts.

Round inserts prolong tool life, Weiss says, "It's the strongest geometry and it thins the

Fig 2. Cylinder-boring tool appearing in Fig 1 (top) features six C4 carbide inserts, four for semifinishing and two for finishing. Polycrystalline-diamond pads guide tool in bore *(Mapal)*

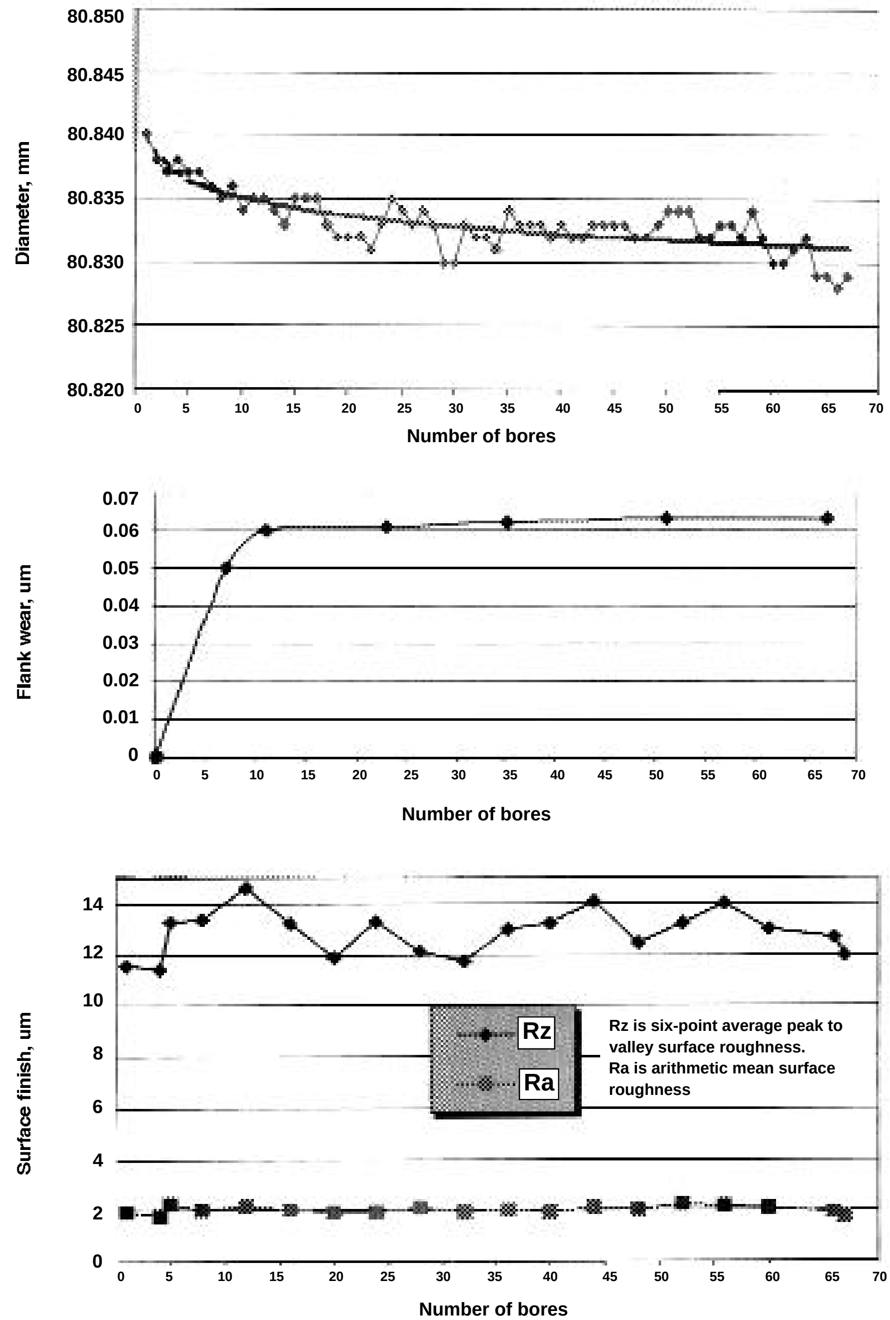


Fig 3. Diameter variance, flank wear and surface finish in cylinder boring CGI with C4 carbide inserts *(Mapal)*

***Table 2. Milling CGI with Si_3N_4 rotating-insert tool*[a]**

	Roughing and semi-finishing	Finishing
Spindle speed, m/min	950 - 1150	950 - 1150
Feedrate, mm/tooth	0.25 - 0.40	0.18 - 0.40
Depth of cut, mm	Up to 6.5	0.18 - 1.0
Typical finish, µm	—	0.2 - 0.5

[a] From Rotary Technologies. Data pertain to using 6-in.-dia tool having seven Si_3N_4 inserts and one CBN wiper insert

chip. The 'roll-shearing' action reduces cutting force and there's no heat, force or stress concentration at any one point on the insert. The load is balanced on each insert, inserts are used on both sides, and they can be reground as many as three times."

For both cylinder boring and face milling CGI, silicon nitride (Si_3N_4) is Rotary Technologies' preffered cutting tool material. Of the eight inserts on the milling tool, one, a wiper, Table 1 gives parameters and results for rough-boring two engine blocks and finish-boring one. General operating parameters for rough- and finish-milling appear in Table 2.

All of the tools noted have been evaluated by the Institute of Production Engineering and Machine Tools (Germany), "using the outside turning of test cylinders to simulate the inside boring operation," according to the Institute's Ulrich Reuter. The Ingersoll and Kennametal tools are for roughing, the Komet is for finishing. Ingersoll's uses nine coated carbide inserts — six for pre-roughing and three for finish-roughing. Kennametal's uses seven coated carbide inserts — four for pre-roughing and three for finish-roughing. The Komet tool uses six coated carbide inserts.

For roughing, speeds (m/min), feeds (mm/min) and machining time (sec/bore) for 2 to 3-mm cutting depth were 618, 1700 and 6 with Rotary Technologies' tool using air coolant; 160, 712, and 14 with the Kennametal. For finishing, using wet coolant and cutting depths of 0.2 mm with the Mapal tool and 0.25 mm with the Komet, they were 120, 676 and 14 with the Mapal and 80, 787 and 13 with the Komet. The aim was a tool-life potential for 500 to 800 bores/workshift. A life of 600 bores was estimated for the Ingersoll tool, more than 1300 for the Mapal and 800 for the others, Reuter reports.

General machining

Just as the mechanical properties of CGI are intermediate between gray and nodular, or ductile, irons, so too is machinability. Thus the reduced fabricability of cast products is a cost burden in choosing the material over gray iron. Sandvik Coromant (Fair Lawn, NJ) has assessed the three irons, using flank wear in milling, turning and drilling with coated carbide inserts as a criterion.

Table 3. Milling and turning CGI[a]

CGI type[b]		Carbide grade[c]	Feedrate, mm/tooth	Speed m/min
	Milling			
Ferritic		GC3020	0.12	175
			0.20	150
			0.30	120
		GC3040	0.12	160
			0.20	135
			0.30	110
Pearlitic		GC3020	0.12	165
			0.20	140
			0.30	115
		GC3040	0.12	150
			0.20	130
			0.30	105
	Turning			
Ferritic		Coromant 3005	0.1	295
			0.3	255
			0.6	200
		Coromant 3015	0.1	280
			0.3	225
			0.6	170
Pearlitic,		Coromant 3005	0.1	250
			0.3	215
			0.6	175
		Coromant 3015	0.1	230
			0.3	190
			0.6	140

[a] From Sandvik Coromant Co
[b] Hardness: 130-190 Bhn for ferritic grade, 200-250 Bhn for pearlitic grade
[c] 3005 and 3015 are TiCN, Al_2O_3 and TiN-coated WC, 3020 is Al_2O_3-coated WC, 3040 is TiCN and Al_2O_3-coated WC.

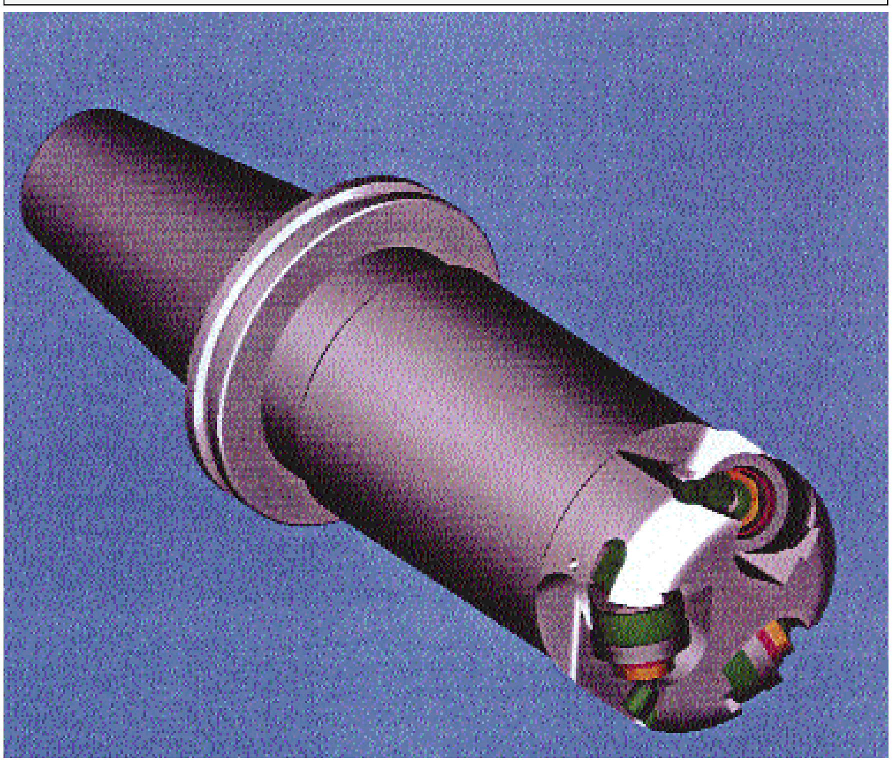


Fig 4. Rotary tool for roughing has three round Si_3N_4 rotating inserts. Another for finishing uses two rotating inserts, and one for milling uses eight *(Rotary Technologies)*

For dry milling at a speed of 150 m/min, a feed of 0.2 mm/tooth and an axial depth of cut of 3 mm, the number of passes for equivalent wear is 21, 40 and 70 for nodular iron, CGI and gray iron, respectively. For dry turning at 250 m/min, 0.4 mm/rev and 2 mm, wear is 0.43, 0.35 and 0.18 mm, respectively. Using coolant, wear in turning is slightly less: 0.39, 0.32 and 0.16 mm, respectively. In drilling with coolant at 80 m/min and 0.1 mm/rev, the wear is 0.2, 0.095 and 0.05 respectively.

"CGI was more difficult to drill than gray iron," says Dr David Upton of Aston Univ (UK), which assessed drilling and tapping with carbides for Ford Motor. For one thing, the flutes were apt to pack with chips and suffer built-up-edge on the cutting lips because of the material's greater ductility, he notes. Also, "Cutting forces were 30 to 50% greater," and torque increased with increasing hole depth, "suggesting lower tool life."

Sandvik offers a variety of coated carbide inserts for milling, turning and drilling CGI as indicated in Tables 3 and 4. Note the variety of coatings: titanium carbonitride, aluminum oxide and titanium nitride, singly, dual or in triplicate, with TiCN always the base coat with multicoatings.

Sumitomo Electric Carbide (Mt Prospect, Ill) has recommended coated carbide and cubic boron nitride (CBN) inserts for milling and turning. At cutting speeds of about 400 sfm, TiCN and Al_2O_3-coated AC300G carbide promises a tool life approaching that in machining gray iron, the company says. ACZ310, which is TiN-and Si_3N_4-coated, was proposed for finish-turning a 1.937-in. diameter at 690 rpm maximum, 350 sfm and 0.003-ipr (2 ipm) feed at 0.010-in. depth of cut over a 0.2-in. length in a single pass with coolant. Cutting time was 0.10 min/part, metal removal rate 0.13 cu in./min, and tool life 300 parts/edge, the latter 186% greater than that of the current carbide insert used.

Regarding CBN, the company has suggest-

Table. 4. Drilling CGI[a]

CGI type[b]	Drill dia, mm	Chipbreaker/ carbide grade[c]	Feed, mm/r	Speed, m/min
Using Coromant U indexable drill R416.2				
Ferritic	12.7-17.0	-53/1120 & -53/1020[d]	0.04-0.10	125-195[e]
	17.5-80.0	-53/4025 & -53/1020[d]	0.08-0.22	125-195[e]
Pearlitic	12.7-17.0	-53/1120 & -53/1020[d]	0.04-0.10	110-180[f]
	17.5-80.0	-53/4025 & -53/1020[d]	0.08-0.22	110-180[f]
Using Coromant Delta drill P411.5				
Ferritic	9.50-14	K20 (1020)	0.15-0.26	55-90
	14.01-17	K20 (1020)	0.20-0.35	55-90
	17.01-30.40	K20 (1020)	0.23-0.41	55-90
Pearlitic	9.50-14	K20 (1020)	0.15-0.25	45-80
	14.01-17	K20 (1020)	0.18-0.33	45-80
	17.01-30.40	K20 (1020)	0.21-0.39	45.80
Using Coromant Delta C drill R415.5				
Ferritic	3.00-5.50	1040 or 1020	0.15-0.25	70-97
	5.51-8.50	1040 or 1020	0.20-0.30	70-97
	8.51-12.70	1040 or 1020	0.25-0.50	70-97
Pearlitic	3.00-5.50	1040 or 1020	0.15-0.25	65-90
	5.51-8.50	1040 or 1020	0.20-0.30	65-90
	8.51-12.70	1040 or 1020	0.25-0.50	65-90

[a] From Sandvik Coromant Co

[b] Hardness: 130-190 Bhn for ferritic grade, 200-250 Bhn for pearlitic grade

[c] 1020 is TiN-coated WC, 1120 is TiCN-coated WC, 4025 is TiCN, Al_2O_3 and TiN-coated WC

[d] Peripheral and central inserts, respectively

[e] For normal conditions; 80-110 for bad conditions and 155-215 for good conditions

[f] For normal conditions; 70-95 for bad conditions and 145-200 for good conditions

ed insert BNX10 for turning with coolant and BN600 for dry milling, both at speeds of 200 to 450 m/min, 0.1 to 0.5-mm/rev feed and 0.1 to 0.4-mm depth of cut.

In tests for automaker Opel, these inserts, respectively, met tool-life requirements in finishing to 20 µm or less and in roughing operations with coolant.