MACHINING GUIDELINES

The ceramic particles—silicon carbide or aluminum oxide—in *DURALCAN* composites (see Figure 1) improve the materials' mechanical properties dramatically, but they also cause tool wear during machining. Silicon carbide (SiC) and aluminum oxide (Al_2O_3) are harder than tungsten carbide (WC) and all other common monolithic tooling materials, except for cubic boron nitride (CBN) and diamond. A practical consequence of this fact is shown in Figure 2.

The information that follows is based on a series of machinability trials using test pieces and actual parts cast from *DURALCAN* F3S.20S* composite or extruded from *DURALCAN* W6A.15A† composite. Most of the work was done on CNC machining centers in a variety of laboratories and factories (see Figure 3).

These guidelines are generally applicable to all *DURALCAN* composites, but they should *not* be extrapolated to other MMCs. For a given tool and cutting condition, the wear rate will depend on five variable features of the composites: the volume fraction, size, and type of ceramic particles, the aluminum matrix alloy, and the heat treatment.

***DURALCAN* composites are not difficult to machine, in the sense of stainless steel, titanium, or nickel-based alloys. With the proper tooling used at the proper settings, they are readily machinable—but the operations are NOT like machining unreinforced aluminum. A vital objective in machining composites is to minimize the wear of the cutting tool by the composites' extremely hard reinforcing particles. Following these guidelines will facilitate that objective.**

MACHINING CHARACTERISTICS

Our machinability trials demonstrate that *by far* the most cost-effective tool material for the production machining of *DURALCAN* composites is diamond. High-speed steel (HSS) tools are dulled in seconds, and conventional and coated carbides last only a few minutes. (Wire and ram electric discharge machining work well, but their parameters vary too much by application to discuss here.)

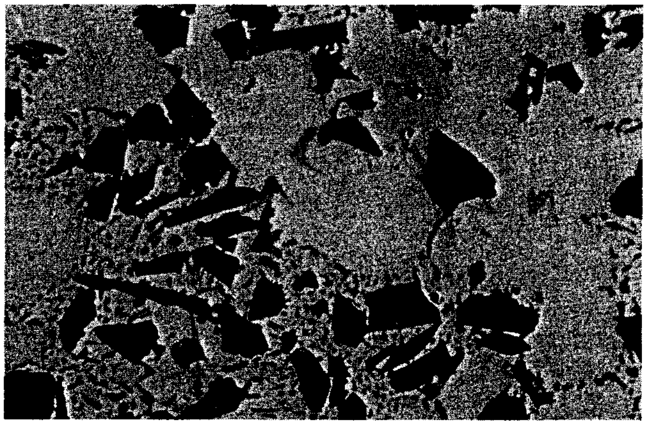

Figure 1 Photomicrograph of a permanent-mold tensile bar cast from *DURALCAN* F3S.20S composite. The large, dark particles embedded in the aluminum matrix are SiC; the small, light ones are eutectic silicon. (500×; scale bar = 20 µm)

The primary mode of tool wear with *DURALCAN* composites is abrasion. As the cutting edge of the tool encounters the ceramic particles in the aluminum matrix, they chip away tiny flakes of the tool edge. (Noncontact processes, such as laser and abrasive waterjet cutting, have little practical application for *DURALCAN* composites.)

The greater the ratio of composite material removed to the contact area swept out by the tool—**i.e., the deeper, wider, or more aggressive the cut—the less the tool abrasion and the greater the tool life.** This concept defines the machining characteristics of *DURALCAN* composites. Compared with a typical aluminum feed rate of 0.13 mm/rev, heavy roughing feed rates not only increase the material removal rate (MRR) but also remove almost twice the volume of composite per unit of tool wear (see Figure 4). (The volume removed equals the product of depth of cut, width of cut, feed rate, cutting speed, and time.)

An even more significant enhancement of tool life is observed when the cutting speed is decreased to below 700 m/min (see Figure 5). This effect is probably due to the lower temperatures and microimpact stresses present in that speed regime.

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* Similar to 359/SiC/20p (ANSI/ASC H35.5-1992 MMC nomenclature).

† Same as 6061/Al_2O_3/15p.

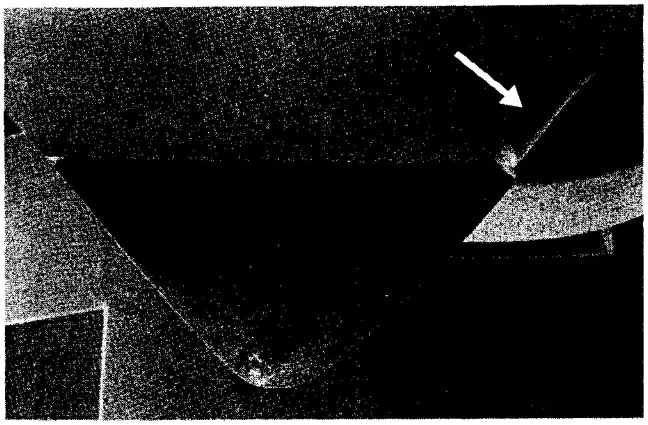

Figure 2 Differential tool wear: WC vs. PCD. Note the depth-of-cut wear groove in the WC body of this PCD-tipped tool, which was run at an excessive DOC. The brazed-on PCD corner exhibits no signs of wear. (7.5×)

TOOL CHARACTERISTICS

Among polycrystalline diamond (PCD) suppliers, product quality and consistency may vary significantly, owing to differences in catalyst levels and diamond-to-diamond bonding. Users fall victim to this problem when they buy PCD tooling based on cost alone.

Consistent quality, predictable tool-change intervals, and lower part-rejection rates are always more cost-effective than cheap tools. For the best results, choose a high-quality PCD source, and specify that the tool maker use only that brand.

We recommend GE Superabrasives Compax 1500 PCD. In addition to the consistent quality of this product (and the excellent customer service available*), its average grain size of ~25 µm offers ~350% greater abrasion resistance than the commonly used grain size of 5–10 µm.

An alternative is to order KD100 tools from Kennametal Inc. (Raleigh, NC), since GE Compax 1500 is the main PCD material used for these tools. This allows end users to work directly with a large, diversified tool fabricator instead of a PCD supplier who produces raw blanks rather than finished tools.

Two other forms of diamond are sometimes available in cutting tools: thick-film and thin-film chemical vapor deposited diamond (CVDD). Thick-film CVDD is similar to PCD in that it is a 0.5-mm sheet brazed to the tip of a carbide tool. Unlike PCD, however, it contains no catalyst material and has 100% bonding between the diamond crystals. Because of this, thick-film CVDD is harder than PCD and may offer superior performance in light-to-medium turning applications. However, it is more susceptible to chipping and is usually unsuitable for milling or other interrupted cutting.

Thin-film CVDD, on the other hand, is directly deposited on the WC tool as a 25-µm-thick layer. Although its performance in milling and other interrupted cuts is presently unknown, high-quality thin-film CVDD (such as KCD25 from Kennametal) may offer equivalent or superior performance to PCD in some turning operations. Other advantages, such as multiple cutting edges, chip-breaking geometries, and rotary tooling, may make this form of diamond more cost-effective than PCD in certain applications.

TURNING AND MILLING

Most machining operations on *DURALCAN* composites require a large-grain-size PCD tool, low speeds, and high feeds. Flood coolant should be applied only if chip clearing or built-up edge (BUE) is a problem. (For prototyping, WC tools [C-1 or ISO K 01] can be used at speeds below 100 m/min with similar feeds and DOCs; however, tool life will typically be <5% of that for PCD tools.)

We recommend roughing at the maximum practical feed rate and DOC, followed by a single finishing pass at a lower feed rate and DOC. For general-purpose roughing, where surface finish is not critical, start at 500 m/min, 0.4 mm/rev, and a 1.5-mm DOC. Under these conditions, one can remove over 30,000 cm^3 (~120 min of cutting) of *DURALCAN* F3S.20S-T71 composite before exhausting the ~0.5-mm-thick PCD layer through wear and resharpening.

Tool wear is more rapid during finishing, owing to the lower feed rate and DOC. The actual settings will depend upon the critical radii of certain features and on the required surface finish. Typical parameters are 600 m/min, 0.13 mm/rev, and a 0.5-mm DOC. Although cutting time is nearly 60 min, less than 4000 cm^3 is removed before the PCD is exhausted.

The DOC should never exceed half of the insert's leg length, and the feed should not exceed half of the nose radius. These precautions will reduce the likelihood of fracture of the PCD cutting edge and of poor surface finish on the workpiece. (Note that the rake and clearance angles for these inserts will generally be the same as for an unreinforced aluminum alloy.)

Figure 3 Machining of a *DURALCAN* F3S.20S-T71 brake rotor during a supplier's proof-of-manufacturing trial.

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*GE Superabrasives regional offices:

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Europe: Wolfgang Taube, 49 (6103) 892-223 (Dreieich, Germany)
The Pacific: Akio Miyagi, 81 (3) 3588-5228 (Tokyo, Japan)

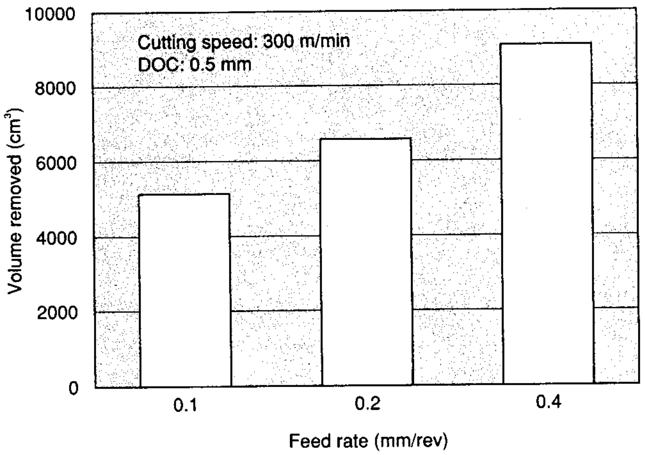

Figure 4 The effect of feed rate on tool life in turning *DURALCAN* F3S.20S composite. (Material removed up to 0.25-mm flank wear.)

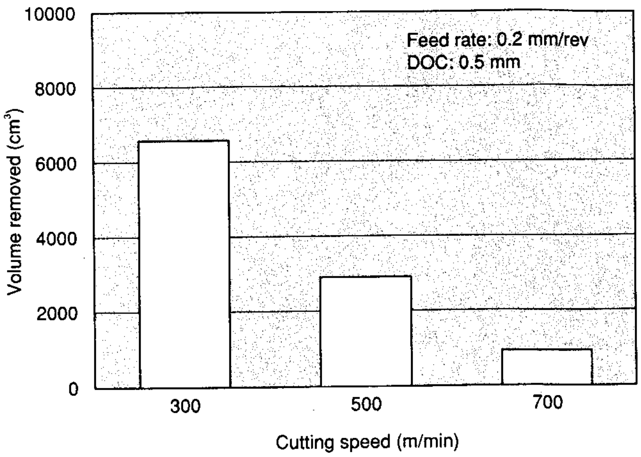

Figure 5 The effect of cutting speed on tool life in turning *DURALCAN* F3S.20S composite. (Material removed up to 0.25-mm flank wear.)

DRILLING AND TAPPING

Drilling

HSS twist drills can *not* be used to drill *DURALCAN* composites. Standard-twist WC-tipped or solid drills are suitable for prototyping. However, PCD-tipped drills should be used in production.

We recommend PCD-veined drills by Precorp (Provo, Utah). Their unique construction offers the ultimate in abrasion resistance, dimensional accuracy, and surface finish. Reaming is usually not required after using these drills.

Because of the abrasive nature of the MMC, point dwell by the drill must be prevented. Adequate feed is essential to drill performance (see Figure 6). For drills 3–15 mm in diameter, a good guideline is to program a feed of $\boldsymbol{d^{1.5}/75}$ (in mm/rev), where *d* is the drill diameter in millimeters.

Evacuation of the abrasive chips is another, more complicated problem. Flute design, point design, and the use of coolant are all important. Coolant-fed drills offer the most effective chip-clearing from deep holes, but flood cooling with 5% water-soluble oil is usually adequate for shallow holes. Point grinds with compound angles and extra relief can break chips into smaller, easier-to-clear curls. Finally, never drill more than three drill diameters deep without retracting the drill to allow chip clearing.

When these problems are properly controlled, drill lifetimes of over 10,000 cm can be achieved with resharpening. (Using the same techniques with carbide drills during prototyping can yield over 250 cm of holes.)

Tapping

Owing to the physical constraints of the process, tapping is the most difficult machining operation with *DURALCAN* composites. **The most cost-effective process for producing threads is form tapping.** Standard HSS form taps can provide over 75 cm of threaded holes (ISO-6H class of fit) at one-third the cost per hole of carbide cutting taps. Although HSS works well for form taps, HSS cutting taps should *never* be used; their high wear rate results in unpredictable tap breakage within the first five holes.

Because additional lubricity is needed, the lubricant ratio should be increased from the usual 1:20 to 1:4 for tapping. On a dedicated tapping machine, specialty tapping oils should be used rather than the water-soluble cutting fluid used in general-purpose CNC machines. Although through-the-tool lubricant is preferred, flood lubricant will also work if applied correctly.

For cutting taps, a fairly low-cobalt, micrograin WC yields the best compromise between wear resistance and rupture strength. A tap with six straight flutes and a plug chamfer offers superior performance, because of its decreased land area, to the more usual three- and four-flute designs. Over 100 cm of holes can be tapped in *DURALCAN* F3S.20S-T6 composite at 200 rpm.

At present, conventional coatings do not significantly improve tap performance. However, diamond-coated carbide taps from Emuge (Northborough, MA) produce up to 1000 cm of threaded holes. With current pricing, the cost per hole is similar to that of plain carbide taps.

Frequent tap and thread inspection is strongly encouraged. Since tap wear occurs on the leading teeth, thread form in the bottom of the hole will usually fail first. In through holes, form taps can compensate for this with an additional revolution or two. But for blind holes or cutting taps, thread wear on the chamfer teeth represents an absolute limit on tool life.

Threads in *DURALCAN* composite will exhibit some "seaming" depending on the tapping method. However, a 65–70% thread (M8×1.25) still exceeds the base material strength with 5–10 threads engaged.

GRINDING AND HONING

Grinding

For form grinding, electroplated industrial-diamond wheels are far superior to any type of ceramic wheel. Thousands of cubic centimeters of composite can be removed without any measurable wear on the diamond wheel. Likewise, the diamond consumables used in conventional lapping and superfinishing operations are suitable for *DURALCAN* composites.

For snagging and offhand grinding, a 50/50 blend of 14-grit black SiC and Al_2O_3 in an R-grade, resinoid-bond wheel of normal structure (e.g., CA14-R9-B5) offers a good balance between MRR and G-ratio (wheel life). Increasing the grinding pressure or selecting a more open structure, a lower bond strength, or a lower grade of wheel will increase the MRR at the expense of wheel life.

Honing

Metal-bonded diamond stones are essential for honing *DURALCAN* composites. Although grit size varies with finish requirements, grit concentration should not exceed C75, to prevent the stones from loading. Stones should not exceed 4 mm in width (unless there are holes, splines, or other interruptions), and the sum of their widths should not exceed 20% of the bore circumference. If guide shoes are required, specify a metal-bonded diamond (with a grit size equal to or finer than that of the cutting stones) or carbide shoe for the best wear resistance and accuracy.

The bore should be flooded with a high-lubricity ("fatty") oil containing extreme-pressure (EP) additives. (Note that EP additives such as chlorine and sulfur should be in the "inactive" form to prevent staining of the workpiece.) Filtering the honing oil below 5 µm is recommended to prevent microscratching of the workpiece by recirculated fines.

Typically, a part (such as a cylinder liner) should first be bored with a diamond cutting tool to within 0.05 mm of finished dimensions. Rough honing with a 150-grit stone for 1–2 min removes 90% of the remaining stock. Finish honing with a 600-grit stone for 30–60 sec removes the final few micrometers of stock and plateaus the surface. (Excessive pressure should be avoided to prevent stone loading. Stroking speed and rotation can be calculated from the desired crosshatch angle, bore diameter, and length.) If additional conditioning is required, a brush-type hone may be useful.

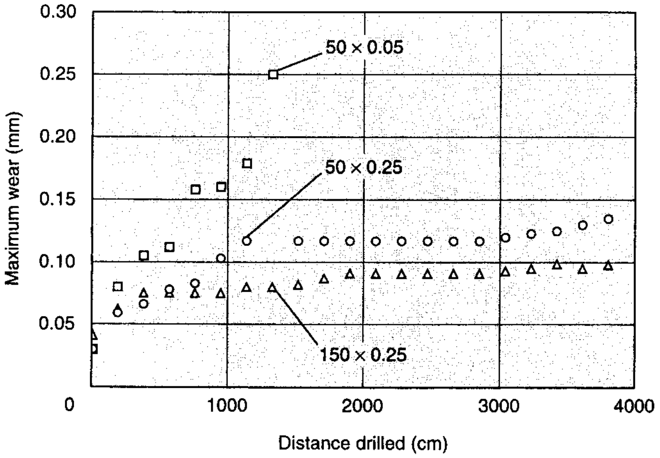

Figure 6 Wear rate of a 6.37-mm-diam Precorp drill in *DURALCAN* F3S.20S-T6 composite as a function of speed (m/min) × feed (mm/rev).

SAWING

For heavy sections of greater than 20 cm^2, we recommend a heavy-duty horizontal band saw with flood cooling (5% water-soluble oil). A WC-tipped blade with ≤1 tooth/cm running at 60–80 m/min with a moderate cutting pressure and feed can make several square meters of cuts at less than \$0.01/cm^2 (depending on the saw capacity and workpiece size). Use the maximum blade thickness and width that the saw is capable of, to reduce blade deflection and improve cut quality. A rotating in-line wire brush combined with a triple-chip or raker-set blade offers the best chip-clearing performance and reduces tooth damage from recut chips. *DURALCAN* billets over 30 cm in diameter are routinely cut in this manner.

New band-saw blades must be seasoned by making four or five cuts each at 50% and 75% of the normal operating speed. The pressure and feed should be kept light (20–30% of the maximum value—similar to that used for low-alloy steels) while the blade is still sharp. As the blade wears, the pressure and feed should be increased to 40–60% of the maximum value (similar to that used for high-speed tool steels). When the blade nears the end of its life, pressure and feed may approach values normally used for stainless steel and nickel-based alloys.

If a blade loses cutting efficiency before its normal lifetime, try the following techniques in the order listed: (1) increase the feed setting by 10% of the full range; (2) increase the pressure by 10% of the full range; (3) increase *or* decrease

DURALCAN Composites MACHINING GUIDE

Tool Materials and Suggested Settings for Typical Jobs

		ROUGHING			FINISHING		
Operation	**Tool Material**	**Geometry**	**Speed (m/min)**	**Feed (mm/rev)**	**Geometry**	**Speed (m/min)**	**Feed (mm/rev)**
Band Sawing	Carbide-tipped	Raker set ≤1 tooth/cm	<70	Medium	35/40-grit diamond	<1500	Medium
Turning & Milling	25-µm PCD* or diamond-coated carbide	Any	<500	>0.3†	Any	<700	>0.1†
Drilling	Precorp PCD* or submicron carbide	118° 4-facet	<150	$d^{1.5}/75$ (d=diam,mm)	—	—	—
Tapping	PM steel*	Forming with lube grooves			4-lobe	<500	—
	Submicron carbide	Cutting with positive rake & relief			6-flute	<300	—

*Preferred choice. †Based on single-point cutting.

This information is intended for general-purpose use only. For more detailed information and legal notice, see parent document, "*DURALCAN* Composites Machining Guidelines," published by Duralcan USA.

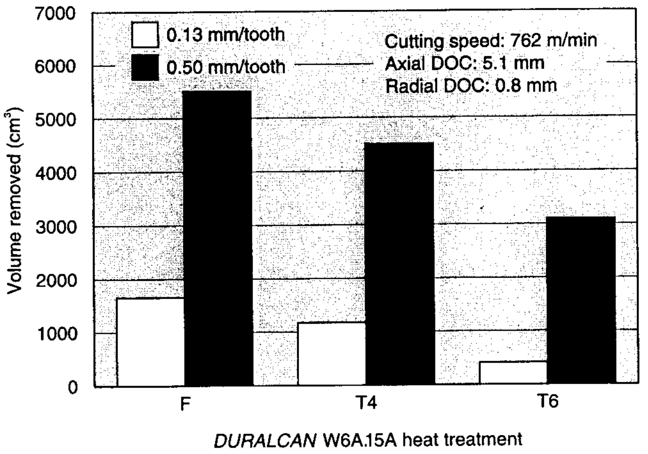

Figure 7 The effect of heat treatment on tool life in the fly cutting of *DURALCAN* W6A.15A composite. (Material removed up to 0.18-mm flank wear.)

the cutting speed by 10% of the current value. If the blade is still not cutting properly after repeating these steps a second time, retract it until the teeth are barely in the kerf. Stop the saw and *carefully* rotate the workpiece 30–60° in the direction opposite the blade motion while maintaining proper blade alignment. Return to the original cutting parameters and restart the saw.

Cold sawing at <60 m/min with WC-tipped or plain HSS circular saw blades can produce similar results. Cold saws have the advantage of being more robust and more easily resharpenable. Circular sawing, like band sawing, requires forced jets of coolants and an in-line rotating wire brush to remove chips. (Mist lubrication does not prevent chip welding and subsequent tooth damage.)

For lighter sections, a vertical band saw with a 35/40-grit industrial-diamond blade and flood coolant delivers the best performance. Blades of this type have cut for over 100 hours at speeds of up to 1500 m/min and are much more cost-effective than WC-tipped blades. Cutoff wheels with edges plated using the same diamond grade perform similarly on hollow sections, but can overheat and lose effectiveness on solid shapes >5 cm^2. For small degating jobs, V-grade resinoid-bond cutoff wheels of 24-grit Al_2O_3 (e.g., A24-V-B5) offer an acceptable G-ratio and MRR.

Four basic sawing guidelines should be observed:

1. For heavy sections, use a WC-tipped blade with low speed, moderate pressure and feed, and flood coolant.
2. Maximize tooth spacing and gullet size while keeping at least three teeth in the kerf.
3. Season a new blade with a few cuts at 50% and 75% of the planned cutting speed.
4. For light sections, use a diamond-grit-edged blade at high speed, moderate pressure and feed, and flood coolant.

WORKPIECE CONSIDERATIONS

Optimum machinability assumes a homogeneous distribution of the reinforcing particles in the aluminum matrix. But when particles are in random clumps or bands, they can damage cutting-tool edges.

Likewise, large particles are more aggressive than small particles. Since wrought *DURALCAN* composites contain particles up to twice as large as those used in the cast composites (but only at the 20% reinforcement level), these wrought composites are significantly more abrasive. This factor even outweighs the extra silicon in the matrix of the cast composites.

Heat Treatment

Although some parts require stress relieving before machining, most parts are machined in the fully heat-treated condition to ensure dimensional accuracy. But this may not always be the best practice. **For example, machining material in an unheat-treated condition can reduce tool wear by more than 50%** (see Figure 7).

For parts that can not be quenched after machining, one compromise may be to solutionize, then machine, and finally artificially age the part to full hardness. In small workpieces, however, heat generated by machining can accelerate aging kinetics so that subsequent artificial aging causes an over-aged condition, reducing yield strength by up to 35%. **Thus, when strength is critical, always machine *after* aging, or modify the aging step.**

Economics

In mass production, machining time far outweighs cutting-tool cost. For conventional aluminum alloys and cast iron, expendable cutting-tool costs are typically less than 5% of the total machining cost. For the composites, tool cost can increase to 30%, but total machining cost still compares favorably to that for machining cast iron, because diamond tools permit equal or faster cutting speeds.

TIPS FOR OPTIMIZING TOOL LIFE

TURNING / MILLING

- Maximize feed and depth of cut within machine limits and finish requirements. This will minimize tool wear.
- To prolong tool life, machine *before* heat treating, if possible.
- Use coolant only if built-up edge (BUE) is severe.

DRILLING / TAPPING

- Do not drill more than 3 diameters deep without retracting to clear chips.
- Directed flood coolant is essential for chip clearing.

SAWING

- Use the maximum blade width and thickness possible to accommodate higher feed pressures.
- Use flood (*not* mist) coolant with an in-line rotating wire brush to prevent chip welding.

GRINDING

- Offhand grinding: best done with resinoid-bond wheel of moderate hardness and normal structure. Typical: 50/50 blend of 14-grit aluminum oxide and black silicon carbide (e.g., CA14-R9-B5).
- Form grinding: can be done only with electroplated diamond wheel with grit size appropriate to finish required.
- Speeds and in-feeds are consistent with grinding aluminum.

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Switching from carbide tools to diamond also changes machining strategy. First, carbide inserts are usually indexed when their wear causes loss of dimension or finish on the workpiece, and are then discarded after the last index. This is also true of thin-film CVDD inserts. However, worn PCD inserts can be resharpened once or twice, though subsequent performance can vary depending on insert condition and resharpening technique.

Second, because of the higher initial cost of diamond, it is more important to program the tool path to use both edges of each corner for additional savings. Finally, the output of multiple-spindle machines is generally limited by the slowest operation. Often, the faster speeds used with diamond tools allow balancing these simultaneous operations, further reducing the cycle time.

SUMMARY

DURALCAN composites are readily machinable, but their ceramic content imposes different tooling requirements from those of unreinforced aluminum. Tool wear, which occurs primarily through abrasion, can be minimized by using slow cutting speeds and high feed rates. By far the most cost-effective cutting-tool material is diamond. Carbide tools should not be used except in operations for which diamond tools do not exist, or for nonproduction tasks such as roughing out prototypes. In either case, it is vital to select tools of high quality and consistency. Tool life can be extended by machining before heat treatment on some parts. Fixturing and CNC programming strategies will be similar to those used for aluminum.

TECHNICAL SUPPORT

Duralcan USA conducts research on the machining and manufacturing of *DURALCAN* composites and provides these data to GE Superabrasives and Kennametal to complement their own research. General questions on the machining characteristics of these composites should be directed to Charles Lane, Program Manager—Machining and Welding Development, at Duralcan USA. Specific questions on cutting-tool design and usage should be directed to Kennametal representatives (see below).

KENNAMETAL

Because the quality and consistency of the diamond products are vital to overall tool performance, Duralcan USA and Kennametal are cooperating to advance diamond machining technology for particulate-reinforced aluminum. (This activity is an extension of the diamond development initiated by GE Superabrasives, which supplies Compax 1500 PCD to Kennametal.) The effort is two-fold:

1. Duralcan USA and Kennametal are developing less-abrasive composites, improved grades of diamond, and optimal machining practices.
2. Kennametal, through its global network of applications engineers, is assisting end users of *DURALCAN* composites in proper tool selection and application, as well as production planning.

The Kennametal network encompasses three geographic regions: the Americas, Europe, and the Pacific. Through the regional offices (below), customers worldwide can request applications support concerning proper tool selection and cutting parameters.

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