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SPECIAL FOCUS:

MAKING AUTOMOTIVE PARTS

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Dry Holes

Dry drilling study.

IonBond Inc.

Drilling aluminum alloys without coolant is certainly feasible. But what about drilling them dry at automotive production rates and at a cost per hole that is less than drilling with coolant?

These queries drove the Big Three automakers and some of their suppliers to establish a consortium to find the answers. (See sidebar, this page, for a list of consortium members.)

The project focused on developing processes to produce high-quality holes in an A-319-aluminum engine block using HSS drills without coolant. Consortium economics dictated that for dry drilling to be feasible, one 6mm drill had to produce at least 10,000 blind holes 20mm deep in the cast aluminum alloy at a spindle speed of 3,000 rpm and a feed of at least 15 ipm.

Drilling without pressurized coolant to eject chips, lubricate the tools and dissipate heat is demanding. The project covered analysis, modeling, tooling, materials and tool coatings.

The analysis was further subdivided into three issues: modeling for distortion, cost benchmarking dry vs. wet machining, and health and safety.

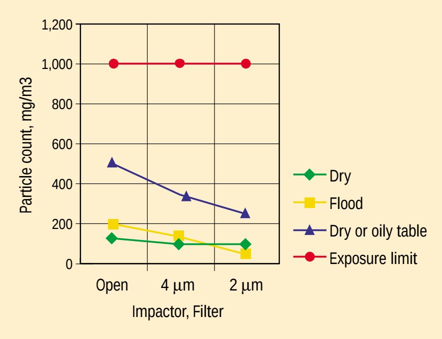
Because dry machining results in higher workpiece and cutting tool temperatures than wet machining, modeling determined the best way to manage thermal distortions. Heat affects the drill's diameter and hole position as the workpiece cools. Furthermore, mathematical modeling can describe these effects and provide guidance on how to optimize hole quality. To help the consortium with this effort, the University of Michigan developed models to evaluate process options.

Hole quality was evaluated in terms of diameter, cylindricity and location. In measuring these parameters, position errors were found to be sensitive to the hole-drilling sequence. Part distortion was found to be sensitive to clamping arrangements and to the effect of friction between chips and the tool.

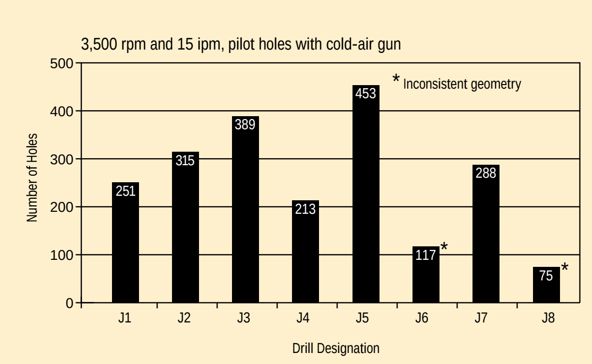
The analysis accurately predicted that dry drilling would produce oversized, bell-shaped holes, and that the drill's thermal characteristics would have a significant impact on hole size and shape. Workpiece material, speeds and feeds played minor roles in determining hole diameter and cylindricity.

A cylinder head was modeled in order to calculate hole-location errors due to the dry drilling's additional heat generation. Drilling forces and torque

The members of the Dry Machining of Aluminum Consortium are **DaimlerChrysler Corp.**, Auburn Hills, Mich., **Ford Motor Co.**, Dearborn, Mich.; and **General Motors Corp.**, Detroit. The supplier-partners are toolmakers **Kennametal Greenfield IPG**, Evans, Ga.; **Kennametal Inc.**, Latrobe, Pa.; machine tool builder **Giddings & Lewis LLC**, Fond du Lac, Wis.; tool-coating producer **IonBond Inc.**, Madison Heights, Mich.; and specialty equipment builder **Extrude Hone**, Irwin, Pa. A formal agreement managed and administered by **Technologies Research Corp.**, Ann Arbor, Mich., a subsidiary of the **National Center for Manufacturing Sciences**, united the team.



Dry machining particle count and size, which are similar to those in wet machining, fall well below the partial exposure limit and thus pose no health or safety hazards.



Drill manufacturing variations affect holemaking capability. Without drills J6 and J8, the variance is by a factor of 2.5.

were measured to determine the amount of heat flux into the workpiece.

A temperature-displacement, finite-element analysis quantified the changes by tracking the locations of eight 12mm and 16 6.4mm holes. The heating cycle started as drilling began and ended when the workpiece cooled to room temperature.

An ideal process was defined as holding maximum location error to ±20µm. Here, the maximum hole-location errors were calculated to be ±37µm for two "worst-case" scenarios: the workpiece slipping in the clamps or operators following an improper drilling sequence.

Modeling showed temperature-dependent drilling errors were small compared to drill walking and runout errors. When distortion from dry drilling is unacceptable, modeling helps to minimize these errors, if the operation is tightly controlled.

To benchmark costs of dry vs. wet machining, Ford, GM and DaimlerChrysler provided data based on machining a typical aluminum engine head on a transfer line with and without coolant. This study showed dry drilling could reduce machining costs per head by 10 to 15 percent compared to wet machining. Moreover, if particulate concentrations attributable to metalcutting decreased from 5.0mg/m^3 to 0.5mg/m^3, as expected, savings would increase by 20 to 30 percent for environmental, health and safety costs.

Recovery of dry aluminum chips is also much more profitable. In 1997, for example, wet aluminum sludge sold for $0.07/lb. to $0.23/lb., whereas dry aluminum sold for $1.05/lb. Operating costs are also less for dry machining. According to the automakers, the annual operating cost of a coolant-based machining system is estimated to be between $350,000 and $1 million. The cost for a dry system is between $100,000 and $300,000.

Money is also saved by not having to expend labor on handling and managing coolant.

In a separate private study, machine tool builder Horkos Corp., Fukuyama, Japan, assessed the relative cost differences among wet, dry and near-dry machining (Table 1). Dry machining was shown to be more cost-effective than near-dry or wet machining. As the data suggests, from a cost-component standpoint, dry machining clearly offers potential rewards that extend beyond just the money saved from not purchasing coolant.

Baseline, Tooling and Process Tests

The consortium examined the effects on hole production of drill walking, cold-air injection, different tool-manufacturing methods, tool geometry, workpiece materials, and speeds and feeds.

Testing commercially available drills' failure rates established the baseline number of holes each drill could produce without coolant. Kennametal IPG provided drills for its tests and Ford's. The Ford spindle ran at 15,000 rpm and the Kennametal IPG spindle ran at 5,000 and 3,000 rpm. Based on the test results (Table 2) a drill with a 45° helix, a 150° drill point and regular-sized land was chosen for design refinement and evaluation testing.

To determine which operational parameter would increase the number of holes produced, the consortium conducted tests covering the following topics:

- workpiece-material consistency;
- drill-manufacturing variations;
- web thinning and polishing;
- effects of higher speeds;
- drill walking;
- cold-air effects;

Cost Component	Relative Cost, $		
	Dry	Near-Dry	Wet
Material: cutting fluid	0	0.33	0.12
Material: liquid waste treatment	0	0	0.08
Labor: mixing, managing coolant supply	0	0.17	0.42
Labor: replacing coolant and cleaning system	0	0	0.46
Overhead: equipment depreciation	0.83	0.83	1.58
Operation: energy consumption, air	0.14	0.14	0
Operation: energy consumption, pumps	0	0	0.58
Total relative cost	0.97	1.47	3.24

Table 1: The relative cost of dry machining is 32 percent less than that of near-dry machining and 69 percent less than that of wet machining.

- ■ shop-air effects;
- ■ equipment enhancements; and
- ■ workpiece suppliers.

Drill performance was defined by the number of holes drilled under the test conditions listed in Table 3 without excessive BUE, breakage or excessive spindle horsepower requirements.

1. *Workpiece-material consistency.* Dry drilling was found to be sensitive to variations in workpiece properties. Inconsistent material properties made repeated tests a statistical necessity for accurate drill evaluation. Variations in workpiece hardness, abrasive inclusions and voids in cast A-319-aluminum workpieces affected the number of holes a drill could produce. Some drills produced two to four times as many holes as others.

2. *Drill-manufacturing variations.* Eight drills, designated J1 through J8, were selected at random from the same manufacturing lot. The drills were tested at 3,500 rpm and 15 ipm using pilot holes to avoid drill walking and a cold-air gun to retard BUE.

Here, the number of holes produced ranged from 75 to 453. By eliminating drills with excessive geometric variations, J6 and J8, the range contracted to a 240-hole difference.

The effect of manufacturing variability was seen in metallurgical tests that IonBond conducted on two seemingly identical drills. One drill failed after 23 holes; the other after 500 holes. Both drills had BUE on the flutes, small cracks near the point, virtually identical microstructures and the same chemical content. The critical difference between the two drills was their point hardness: one was 9 percent below design value and the other was 19 percent below. However, at 100µm from the point, drill-point hardness equaled design value.

Further analysis determined that improper tool grinding softened the points. This situation illustrates why correct point geometry and optimal physical properties of the tool material are critical to performance.

3. *Web thinning and polishing.* One batch of drills underwent an additional web-thinning operation to demonstrate how more flute space for chip evacuation mitigates chip-packing failure. Another batch with the same geometry had its flute surfaces polished to lower the coefficient of friction between the chips and the tool. Kennametal IPG refers to these polished drills as “bright.”

Web thinning increased hole production significantly compared to polishing. The best production occurred with a web-thinned drill rotating at 3,500 rpm and fed at 15 ipm.

4. *Effects of higher speeds.* The lower chip loads at higher speeds and constant feeds increased the hole production in the absence of coolant.

5. *Drill walking.* Slight imperfec-

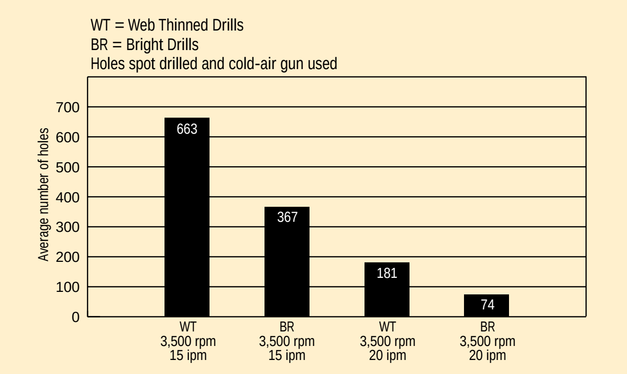
Helix Angle/ Point Angle/ Land Size (Small or Regular)	**Ford Spindle**		**Kennametal IPG Spindle**			
	15,000 rpm		**5,000 rpm**		**3,000 rpm**	
	Feed, ipm	**# Holes**	**Feed, ipm**	**# Holes**	**Feed, ipm**	**# Holes**
18/90/S	75	16	25	19	15	23
	150	12	50	6	30	4
	225	5	75	4	45	2
18/90/R	75	12	25	14	15	15
	150	13	50	6	30	5
	225	8	75	5	45	3
18/150/S	75	12	25	13	15	30
	150	17	50	6	30	8
	225	5	75	4	45	6
18/150/R	75	12	25	15	15	20
	150	23	50	7	30	10
	225	12	75	9	45	7
45/90/S	75	18	25	28	15	52
	150	16	50	22	30	19
	225	18	75	15	45	10
45/90/R	75	9	25	12	15	12
	150	5	50	11	30	9
	225	23	75	10	45	4
45/150/R	75	14	25	100	15	98
	150	5	50	67	30	53
	225	10	75	42	45	30

Note: All were uncoated, HSS, 6.75mm-dia., 100mm-long drills.

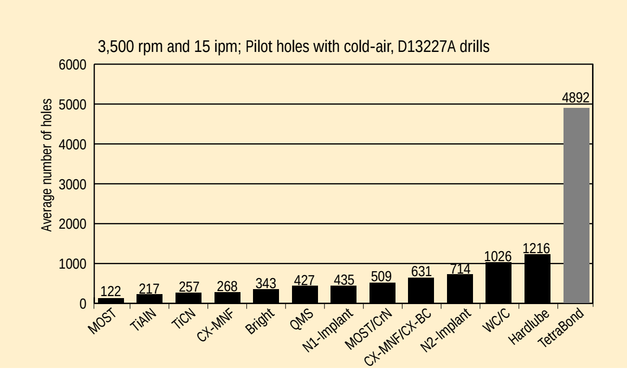
Table 2: In the baseline tests, one drill, the 45/150/R, exhibited superior capability in the number of holes drilled in cast the A-319-aluminum alloy.

Test Parameter	**Test Condition**
Spot drill	5/32" dia., screw-machine length, 118° point, 0.050" depth
Test drill	6.75mm dia., 145° point, 45° helix, 120-grit flute finish, regular land
Hole depth	0.800" blind hole
Speed & feed	3,000 rpm at 15 ipm
Cooling	None or with an Exair Corp. “cold gun”
Material	Cast A-319 aluminum from M&A Foundry
Hardness	48 ±6 HBN
Metallurgy	Al 90.18 percent (5.80 percent Si, 3.80 percent Cu, 0.10 percent Fe, and 0.12 percent Ti)

Table 3: Kennametal IPG used fixed test conditions in seeking hole productivity improvements.



Comparison between web-thinned drill and similar drills with polished flutes shows that web thinning increases holemaking capability.



PVD diamond-like coating (TetraBond) on drill points provides superior holemaking capability, compared to 12 other coatings.

tions in drill points and spindle runout cause drill points to move in small, nearly circular orbits. If the orbit is large enough, the point tends to walk on the workpiece surface before biting in. Walking creates stresses that shorten drill life. Generally, drill walking was eliminated by spot drilling a 5⁄32"-dia., 0.05"-deep pilot hole. This increased the number of holes from 36 to 52.

Drill Mfr.	Coating	Dia.	# Holes	Comments
Guhring	TiN	0.375"	55	Cold air through drill
Kennametal IPG	PVD-DLC	0.265"	98	No delay between holes
		0.265"	119	5-min. delay after 13 holes
		0.265"	162	Cold air flooded on drill

Table 4: HSS drills running at 3,000 rpm and 15 ipm are capable of drilling more holes when their points are cooled by cold air.

6. *Cold-air effects.* Comparisons were made for two types of cold-air-delivery methods. Through-the-tool delivery of cold air and via external nozzles directed at and near the drill point reduced BUE. While the number of holes increased from 55 with air flowing through the tool to 162 with air directed at the drill point (Table 4), the end result fell well short of the 10,000-hole goal. In addition, the cost of cold air was high compared to tool-replacement costs. Consequently, the introduction of cold air did not cause a significant improvement and was dropped from further evaluation.

7. *Shop-air effects.* Filtered, 90-psi shop air was ported through the spindle and tool. The material tested was A-319-aluminum waffle plates from DaimlerChrysler. The drill was a 6.75mm-dia., HSS, 2-flute tool. The spindle speeds were 3,000 rpm and 15,000 rpm, and the feeds were 15 ipm and 225 ipm. With no air, a spindle speed of 3,000 rpm and a feed of 15 ipm, the drill broke on the 38th hole. With air, the drill broke on the 624th hole. With no air and a speed of 15,000 rpm and 225-ipm feed, the drilling machine became torque-limited during the 23rd hole. With air, the torque limit was stretched to the 34th hole.

Under some operating conditions, air-through-the-tool cooling is beneficial to holemaking. However, the low feed rates defeated the project's high-throughput objectives.

The influence of air on chip removal and heat transfer was minimal because the air mass passing through a drill was small. Through-the-spindle air—even cold air—could not be cost-justified.

8. *Equipment enhancements.* Equipment enhancements included a 20,000-rpm spindle, an ultrasonic-assisted vibrating head attached to the drill, inverting the spindle to run nose up and shrouding the tool within a vacuum. These enhancements, however, did not produce encouraging results and were likewise abandoned.

9. *Workpiece suppliers.* Repetitive tests showed that different casting suppliers delivered workpieces with noticeably different physical properties for the same specifications. This strongly influenced drilling productivity. By eliminating, or substantially reducing, the variation among material suppliers, drilling three to four times the number of holes would be possible.

The additional stresses and deflection that occur when drills encounter voids, inclusions and hardness variations on an already-stressed drill were significant. Thus, ensuring and maintaining casting quality among suppliers and material consistency within an aluminum casting is essential to achieving high productivity with optimized drills.

Tool Coatings

Tool coatings offered the most effective means for attaining high productivity when machining dry in the consortium's test program. Comparatively, uncoated drills performed poorly, rarely exceeding 25 holes before failure.

The most promising coating tested was a physical-vapor-deposition, diamond-like coating applied only to the drill point and the rake faces, as opposed to the entire flute surfaces.

Web-thinned, regular-land drills with a 45° helix, 150° point and PVD-coated tip were compared with 12 other commercial drills of the same configuration, but without web thinning and coated with various surface treatments. The spindle speed and feed were 3,500 rpm and 15 ipm, which, in light of other tests, may have been too slow. Here, the partial PVD diamond coating proved to be superior, enabling the drill to produce 4,892 holes.

These drills, however, failed due to wear—not chip packing or chip buildup. Based on these results, therefore, a web-thinned, bright, 45°-helix, 150°-point, regular-land drill with a PVD-coated-tip running at 15 ipm and 4,000 rpm was projected by the consortium to reach 8,000 of the targeted 10,000 holes.

The maximum number of holes produced during this project, however, does not appear to represent the upper limit. Tests of varying speeds and feeds indicated that improvements are possible, if the speed is raised from 3,000 to 4,000 rpm. Furthermore, edge treatments may enable drills to attain 100 percent of the goal.

Clearly, the technology for dry drilling in A-319 is not yet robust enough to make the process economically feasible at automotive production rates. However, as is obvious from the numerous and thorough tests undertaken by the consortium, great strides in advancing the technology have been made, clearing the path for further improvements. Economic feasibility, therefore, may be just around the corner.

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