Many companies covered by the proposed rules will have to choose between substantial outlays and shutting down operations covered by the rules

Performance Experience With Near-Dry Machining of Aluminu

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Note: This report reproduced as printed and presented at the STLE 56th Annual Meeting in Orlando, FL, May 20-24, 2001

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ABSTRACT

In dry machining of aluminum alloys, only two processes that offer near-term solutions for automotive applications appear feasible. One of these processes uses a minimum quantity of lubrication and is referred to as “near-dry.” By feeding an air/oil mixture through channels in a cutting tool, a partial boundary lubrication condition is established. Compared to dry machining, near-dry machining substantially enhances cutting performance and uses so little lubricant that machined chips look and feel dry. In use, drilling has proven to be a critical operation: chip evacuation, chip adhesion to the drill, and drill wear are major issues. This paper discusses these issues as they relate to the machining of an automotive cast aluminum production part. Data is presented on machining accuracy and on the amount of lubricant and air required by the 11 tools used to produce the features of this part in a cycle time of about 2.5 mm.

THE CHALLENGE OF MACHINING ALUMINUM DRY

In a high-volume manufacturing facility, the total cost of using machining coolants is high and is increasing as health issues squeeze mist regulations tighter and tighter. There are, of course, maintenance requirements to consider. Coolant contamination and chemical balance are constant maintenance concerns and, in a large plant, the real estate consumed by vast coolant systems adds an unwelcome space charge to the cost of the plant’s products. All in all, there are many compelling reasons to eliminate coolant and find means for machining dry. However, coolant does quadruple duty:

- It cools the tools so they do not lose their strength.
- It cools the workpiece so it does not distort excessively.
- It flushes away chips so the tools and the workpiece are not damaged.
- And, most importantly, it lubricates the cutting tools to retard wear and heat generation.

The challenge for machining dry is to provide substitutes for these four critical functions. That such substitutions can be done economically in industrial applications is not obvious.

Some materials lend themselves to dry machining—but not aluminum. Some machining operations are easier to deal with—but drilling is not one of them. In drilling with coolant, drills are retired because of wear. In drilling without coolant, drills often fall because their flutes become packed with chips, causing the drill to break as it grows hotter and falls in shear. It is not surprising that drilling blind holes in aluminum is rated very high in degree of difficulty if it is done without high pressure coolant delivered through the tool.

In a recent privately funded project on dry machining of aluminum, one of the goals was to seek the design and manufacturing parameters that would allow a 6-millimeter (mm), high-speed steel twist drill to produce 10,000 blind holes, 20 mm deep in A3 19 aluminum. To establish a baseline, a number of uncoated drill configurations were tested; none could drill more than 25 holes. Basically, the drills failed because chips adhered to the drill and blocked the free discharge of chips, causing the shear stress on the drill to increase until it broke.

Coating the drills with a variety of standard products and implementing several application methods raised the hole producing capability of twist drills to approximately 225 holes, still a long way from the target of 10,000 holes. Over the course of the project, many features of the drill and the drill manufacturing process were found that could be optimized, and this group of changes raised the hole-producing capability to about 650 holes. Toward the end of the project, a breakthrough was discovered. A coating and a special coating procedure were developed that raised the number of holes that could be drilled to almost 5,000. The drill used in this procedure failed from wear and not from chip packing.

The dry machining project team believed that yet-unexplored changes could raise hole production to about 8,000, but the 5,000 holes achieved through this project are believed to represent the state of the art for dry drilling of aluminum. For comparison, a standard production drill was provided with a low flow of air/oil mist and tested in the same facility used for the dry testing. After 10,000 holes, the drill was still producing quality holes and would eventually be discarded due to wear. This comparative experience made clear the production advantages that could come from lubricating cutting tools. However, a solution that produces an oil mist creates its own problems that often offset its benefits.

THE CONCEPT OF MINIMUM-QUANTITY LUBRICATION

The message is clear: by lubricating the parts that rub during cutting, drill life can be extended substantially, provided some drill design and manufacturing precautions are taken; these will be discussed later. Due to the geometry, cutting load and relative motion, there is no practical way of generating a full fluid film between the cutter and workpiece, neither hydrodynamically nor hydrostatically. What can be done is to provide boundary lubrication, or at least partial boundary lubrication. As is well known from many lubrication studies, the quantity of lubricant to achieve boundary lubrication is small—compared to flow rate for a pressurized coolant feed drill, the quantity is indeed very small. Coolant flow is measured in liters per minute; flow for boundary lubrication is measured in milliliters per hour. One system requires pumps, tanks, filters, piping, valves, and continual maintenance. The other system requires about a 4-liter (L) container and lubricant injectors. The small amount of lubricant that is discharged into the space surrounding the tool is typically captured by a mist collector system. Because fluid cannot be seen in the work zone, and because the chips look and fee! dry, this application of minimum-quantity lubrication is called “near-dry” machining. -

The lubricant can be a vegetable oil or some other lubricating liquid that provides an environmental advantage. Compressed air is the delivery vehicle. Since compressed air is an expensive commodity, the amount used is controlled and minimized. The air/oil mixture reaches the cutting zone through one or more holes through the drill. Through-the-tool coolant passages are common in production drills. However, in near-dry drilling, the holes act as orifices to control the air/oil flow rate and, because the "fluid" is air and not a liquid, the hole size is not the same as it would be for through-the-tool coolant applications. Consequently, drills must be designed and manufactured expressly for near-dry applications. Otherwise, the drill will not meter the correct air/oil flow, and either tool wear or the amount of oil used will be excessive.

A critical issue for near-dry drilling is how and where the mixing of air and oil takes place. In some designs, the mixing is done outside the spindle. This approach has a low first cost, but not the lowest life-cycle cost. An external mixing device can be serviced readily, and only one rotary seal is needed in the spindle. However, spindle rotation creates a centrifugal force field that will coat the walls of the delivery tube with oil that must be removed periodically. For a high-volume production factory, the downtime may be intolerable.

A more desirable concept, shown in Fig. 1, is to mix the air and oil as close as possible to the drill in a well-designed mixing chamber. The design of the mixing arrangement is so critical that several machine tool companies have patented their designs. In implementing this two-tube approach, two issues need to be addressed:

- Two nested rotary couplings must be provided for the air and oil connections, which raises questions regarding reliability and durability.

- The system plumbing must be prevented from shifting and changing the spindle's residual unbalance. As spindle speeds increase, both these design issues become more of a problem.

At least three machine tool builders have worked out all the design issues and now offer machine tools that incorporate near-dry machining technology. In doing so, they have also addressed one of the most critical requirements for low maintenance dry machining—chip evacuation and collection. Recently, one of these builders has delivered high-speed machining centers equipped with near-dry technology to a Ford factory in Cologne, Germany. Twelve of these machines are using near-dry technology to produce clutch and transmission housings (Fenauer and Stoll). As the environmental and economic benefits become well established, these primarily wet factories are expected to shed their coolant and dry out little by little. The same view is apparently shared in Japan where machine tools with near-dry technology are being re-ordered by some of Japan's largest automotive companies. However, there are many process options and very little research on which options offer the greatest economic benefits

THE PROBLEM OF CHIP EVACUATION AND COLLECTION

Smooth, continuous chip evacuation while drilling a hole depends on the friction between the chips and the drill as well as the size and configuration of the chip. Polishing the flute surfaces proved to be an effective way of reducing friction, and coating the drill with a hard material proved very effective in increasing drill life. However, care must be taken when the drill is coated because many coating processes result in a rough surface, which nullifies the benefits of flute polishing.

High-pressure coolant is effective in ejecting chips from the drill. In dry drilling, air replaces liquid; but in a practical design, air cannot produce the ejection force that a liquid can exert. Consequently, the chips must be made more ejectable, which means making them smaller and more curled. This requirement can be met satisfactorily by optimizing the drill geometry, the speed, and the feed.

Even if the chips are removed from a drilled hole, they must still be removed from the cutting zone and into a collection hopper. Otherwise, they will damage the tool, the workpiece, or the machine tool. The worktable mechanism offers one of the ways of moving chips to a collection mechanism. In some designs, the table mechanism flips the workpiece from an upright position for loading to an upside-down position for machining. The flipping throws off the stray chips that collect on the fixture and worktable, and the majority of machined chips will fall down onto a chip conveyor belt that is built into the base of the machine.

Another design necessity for avoiding unnecessary machine downtime for cleanup is to make the walls of all interior surfaces steep enough so that the chips will slide down and drop onto the chip conveyor belt. Some machine designs offer blowers that can blast loose the chips that adhered to the wall. The blowers enable the machine to be cleaned automatically without opening the machine hood.

From the steps that must be taken to implement cutting tool lubrication and chip disposal, it is apparent that near-dry machining of aluminum requires a machine tool and cutting tools that are designed specifically for near-dry machining. Based on the differences between a machine designed for cutting with coolant and a machine designed to operate without coolant, retrofitting an existing machine does not appear to be an attractive alternative. One of the principal issues is that the base of a retrofitted machine is likely to have many crevices, and chips would collect quickly, requiring continual operator intervention to remove them. However, several machine tools have been retrofitted with near-dry technology. The users have elected to deal with the inconvenience because they judged the gains as outweighing the disadvantages.

MACHINE TOOL SELECTION

To evaluate near-dry machining as a viable process for high-volume production of aluminum parts, the project team reviewed three machine tools and purchased one as the test vehicle. The team made its selection primarily because the machine incorporated two features of interest in addition to implementing near-dry technology. One of these features is a vacuum system that works in conjunction with tool shrouds to capture chips and dust at the cutters and pipe them to a collection system. Fig. 2 shows a photograph of a shrouded tool. Fig. 3 shows the operating concept. The other feature of interest was that the near-dry implementation equipment mounted inside the spindle could be removed and replaced with a high-pressure coolant system. Using this feature, the team could make a direct comparison between wet and dry production of the same part. Some specifications of the selected machine are:

- 15,000-r/min spindle
- 500 x 400 x 500-mm table
- Vacuum chip removal system
- 15-kilowatt (kW) alternating current spindle motor
- Vertical rotary changer turning over 1800

- 7-megapascal (MPa) through-the-tool coolant system
- HSK-A63 spindle nose
- 24-position automatic tool change
- 3-second (s) chip-to-chip changer
- Air—oil spindle lubrication
- Polymer-concrete-filled' structural elements.

TEST PLAN

The evaluation procedure consists of four sets of tests. The objective of the first test set was to assess the capabilities of the near-dry machining system without the vacuum system. These tests, including the initial trial period, were conducted over a matter of weeks and ended with the formal equipment acceptance tests. The acceptance tests for the project's machine were completed in the machine tool builder's facility using an aluminum bracket test part provided by the project. A coordinate measurement machine (CMM) was used to inspect the machined part. The part, shown in Fig. 4, is a bracket for an engine mounting strut made from cast aluminum alloy. Representatives from the project team were present for part of the test program, which included a runoff and inspection of 50 parts. The full team reviewed the results and determined that they complied with project requirements. These results are summarized below under the "Test Results" section.

The second set of tests incorporated the chip vacuum system and the shrouded too! set. The same part and the same inspection system were used to assess the performance of the vacuum system. After the vacuum tests were completed, the near-dry implementation components were removed from the spindle, and the third set of tests was run using the through-the-tool, high-pressure coolant arrangement. The fourth set of tests, now in progress, is focused on long-term considerations such as tool wear and maintenance requirements. Tool wear studies will include thousands of parts and will provide information on lubrication and chip collection performance. These tests will take place over a 12-month period. To test the robustness and acceptability of the equipment and process, a Tier I supplier to the automotive industry was selected as a project team member to perform the machining. The Tier I supplier is a high-volume producer of parts to the automotive manufacturer. One of these parts is the bracket selected as the first test part.

The machine tool was installed February 2001 in the Tier I supplier's facility, where supplier personnel are machining the parts and running the test program. Since the supplier has been producing the bracket part with a wet process, the supplier has records for the machining cost, cycle time, tooling requirements, and maintenance actions. These records are a valuable source of data for comparing past production methods with the near-dry machining process.

RUNOFF TEST GOALS

The purpose of the runoff was two-fold:

- To show that the machine tool could produce the test part within tolerances
- To measure the lubricant and air flow rates.

Prior to runoff, about 100 parts were machined to debug the machine and set up the machining process for the bracket part. No data was taken during this period. Since the runoff was scheduled to process 50 consecutive parts without a system failure, meaningful data on tool wear and maintenance could not be obtained from the runoff tests.

The machining process designed by the machine tool builder used two part-holding fixtures and executed 11 operations. The machining consisted of surface milling, drilling, tapping, and side milling. The side-milling operation was performed with a tool that has two parallel cutters fitted with side-cutting inserts. This tool milled the two bracket arms simultaneously to achieve a specified distance between the arms. The machining goals for the runoff were:

- Mill the datum and mounting surfaces to less than 70% of the allowable tolerances.
- Drill and position all holes to a Cpk (definition given below) > 1.67.
- Tap holes in accordance with the specifications for tap classes 6H and 10H.
- Hold the spacing between the two bracket arms to a Cpk > 1.67.

Cp and Cpk are statistical parameters that characterize the process potential and actual process accuracy. Cp is basically a ratio of the part specifications to the process capability. It is obtained by subtracting the lower specification limit from the upper limit and dividing by the quantity “6” Sigma is the standard deviation for the process. The quantity “6” is taken as the natural tolerance capability of the process that should contain nearly all the process variation measurements from a group of parts.

Cpk is a similar ratio that takes into account the distance between the midpoint of the upper and lower specification limits and the location of the mean of the process variations. It is a measure of how well the process is centered between the specification limits. If the distribution of process variations is centered between the upper and lower specification limits, Cp = Cpk; if the process is not centered, Cpk < Cp. If Cp, < 1.0, some of the process variations exceed the specifications—these are defective parts. If Cp = 1.0, the variations are just meeting the specification. If Cp> 1.0, all the variations lie inside the specification limits.

For high-quality, “6” manufacturing, Cp should be 2.0 or greater, and Cpk should be 1.5 or greater. For the runoff, the goal for all features with an upper and lower specification limit was Cpk > 1.67. Meeting this goal would indicate an accurate machine and an accurate, well-centered process.

Prior to the runoff, the theoretical lubricant flow, air flow, and process cycle time required for each of the 11 operations were calculated. The total predicted quantities per part were:

- 0.0001478 L (0.005 fluid ounces)
- 0.0172 cubic meters (in3) (0.607 cubic feet)
- 2.173-minute (mm) cycle time.

Based on these values, the total lubricant used over an 8-hour (h) shift producing one part every 2.2 min would be 32 milliliters (mL), and the total amount of air under standard conditions would be 3.75 m3. These forecasted values are low. Meeting them would make the concept of near-dry machining feasible, at least with regard to short-term performance.

TEST RESULTS

Near-Dry Machining Without Vacuum

The critical test results are the computed values for Cp and Cpk using measured data taken for all 50 runoff parts. These values are given in

Table 1. For every operation, a number of measurements may have been taken. For example, for a drilling operation, the diameter and two or more position location measurements were taken. Both the diameter and the location are reported in Table 1. For datum and mounting surfaces that have single-sided specification limits and multiple measurements, the lowest value of Cp is given in Table 1. Table 2 compares the cycle time and the total quantity of lubricant and air required to produce a part. At the conclusion of the runoff tests, the cutting tools were inspected and no significant wear was observed.

Near-Dry Machining With Vacuum

The near-dry machining tests with vacuum consisted of an 80-part runoff in which Cp and Cpk were computed for all parts. As can be seen from Table 1, the Cpk values for all operations met the goals. On average, the Cpk values for machining with and without vacuum are 7.64 and 8.20, respectively. Essentially, the difference between the two processes is that the shrouded tools and vacuum system prevent chips, dust, and mist from escaping the immediate vicinity of the cutting zone while the non-vacuum system depends on the mist collection system and gravity to dispose of the chips, dust, and mist. Table 2 shows that the use of a vacuum increases the cycle time because of the weight of the shrouds.

Conversion to Wet Machining

As part of the machine demonstration at the builder’s facility, the machine was converted to implement a high-pressure, through-the-tool coolant process. The purpose of these tests was to show that the conversion can be accomplished without difficulty and that the system functions properly. The process was optimized to obtain an accurate cycle time minimum.

The wet machining test consisted of an 80-part runoff in which Cp and Cpk were computed for all parts and found to be similar to both near-dry runoff tests. The measured cycle time was 2.50 mm, which was equal to the dry-process no-vacuum cycle time.

Table 1 shows that the Cpk values for wet machining also met the goals. The average Cpk value for all the operations is 8.05, which is similar to the results from the other tests

.Long-Term Tests

Testing is scheduled to last 12 months. During that period, currently in progress, data will be collected on tool wear, process reliability, durability and robustness, and maintenance requirements. A daily log will be kept and photographs will be taken periodically to assess any buildup that occurs in the machine. About one-third of the parts will be machined without vacuum, one-third with vacuum, and one-third with high-pressure coolant. Following the testing, the costs and benefits of each of the three processes will be evaluated and tabulated.

CONCLUSIONS

To date, performance experience with near-dry machining has shown that lubricating the cutting tools significantly reduces tool wear and allows some parts to be manufactured that previously could not be machined economically without coolant.

Near-dry processes appear to offer an economic advantage over completely dry machining of current aluminum alloys where drilling with twist drills is required. However, switching between wet and dry operations on the same part is not economically feasible with current technology. If near-dry processes are to be used, then near-dry machining must produce all the features on a part.

The test machine was operated in three different modes: with minimum-quantity lubrication (MQL, a synonym for near-dry) only; with MQL, tool shrouds, and vacuum; and with high-pressure coolant. For the three modes, 210 units of the same part were machined (50, 80, and 80, respectively). All parts were inspected on a CMM and the statistical process parameters Cp and Cpk were computed. The results indicate that parts of high quality can be made in any of the three modes. The issue now is: What changes will take place with time and use?

Chip management is also an open issue that cannot be answered until longer tests are completed and analyzed. However, the machine tool builder claims that the experience of its customers in the automotive field indicated that chip management is an issue, but not a critical one.

Near-dry machining in production has been demonstrated successfully, especially in Germany and Japan. Both countries have invested years in experimental development to establish their technology and integrate it with machine tools. However, the technology is still new, especially in the U.S., and issues such as tool wear, machine reliability, and maintenance requirements remain open-ended. Consequently, so does process economics.

ACKNOWLEDGMENTS

The data for this paper was from a project sponsored by the U.S. Department of Defense Commercial Technologies for Maintenance Activities program (CTMA)I Defense Logistics Agency, and cost shared by a team of participants. The content does not necessarily reflect the government's position or policy; no official endorsement should be inferred.

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Collaborative CTMA Project Team

- DaimlerChrysler Corporation, potential technology user
- Ford Motor Company, potential technology user
- General Motors Corporation, potential technology user and supplier of test parts
- Kennametal IPG, potential technology user and provider of tooling and tooling analysis
- Machining Enterprises, Incorporated, facility in charge of and site of long-term machining tests
- Marubeni America Corporation, distributor of the HORKOS machine tool selected for the project
- National Center for Manufacturing Sciences, project manager
- U.S. Naval Aviation Depot, Cherry Point, North Carolina, potential technology user.

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