Robotic Automated Deburring of Aerospace Gears

Michael Nanlawala

Introduction

This report presents some interim results from an ongoing project being performed by INFAC, the Instrumented Factory for Gears. The purposes of this initial phase of the project were to demonstrate the feasibility of robotic automated deburring of aerospace gears, and to develop a research agenda for future work in that area.

Deburring of machined metal parts, such as gears, is a costly and labor-intensive process with associated quality, consistency and health risks. It is a particular problem and a major cost driver for gears that are considered aerospace- or precision-grade (AGMA Class 12 and above).

Wherever possible, gears are deburred by using simple mechanical equipment that is commercially available. However, complex gears that have specific chamfering requirements, as do precision-grade gears, must currently be deburred manually (Figure 1).

Manual deburring is not only a labor-intensive process, but it is also associated with the quality problems resulting from inconsistent manual operation; health-, safety- and environmental-related issues; and high indirect costs as a result of a high turnover of operators.

Automation of the deburring process can significantly reduce cost, improve productivity, and improve the quality and consistency of deburred edges. This situation has led to an industry-wide demand to replace manual deburring with a more efficient, reliable, and safer automated deburring system. The INFAC Robotic Automated Deburring research project was initiated to address that need. It is a joint technical effort being conducted by IIT Research Institute, United Technologies Sikorsky Aircraft, and United Technologies Research Center.

Using the robotic automated deburring system developed under the project, the INFAC team has successfully deburred a number of aerospace gears, ranging in size from 3 inches to 30 inches in diameter. The system uses commercially available, off-the-shelf hardware, including a six-axis programmable robot, a programmable index table, various types of deburring heads, and several different types of cutters.

Fig. 1—Manual deburring is labor-intensive, inconsistent and expensive.

In addition to cost savings that, in some cases, exceeded 90 percent and substantial quality improvements, such an automated deburring system can eliminate potentially unsafe and relatively unhealthy working conditions. The system enables computer control and automation to be applied to the deburring processes, bringing it at last into the domain of computer integrated manufacturing.

Background

Machining processes, such as milling, drilling, turning, hobbing, or other gear tooth cutting operations, create burrs on the edges of metal parts when the cutting tool pushes material over an edge rather than cutting cleanly through the material. The size, shape and characteristics of the resulting burrs depend upon a number of process factors, such as tool material and its hardness, tool sharpness, tool geometry, cutting forces, ductility of the material being machined, the speed and feed of the cutting tool, and the depth of cut. A subsequent deburring operation is generally required after those machining processes to remove loose burrs from the machined edge and to apply a chamfer to remove the sharp corners. In addition to the removal of loose burrs, the deburring of the edge produces benefits, such as the removal of sharp edges, increasing the ease of assembly, prevention of edge chipping or breakage, and improvement of air flow over the edge of rotating parts. Removing sharp edges by deburring and chamfering also eliminates the possibili-

Michael Nanlawala

has more than 25 years of experience in manufacturing commercial-quality and aerospace-quality (ground tooth) gears of almost all types. He has been working as a senior engineer for IIT Research Institute for more than five years and has been actively engaged in various research projects to improve the quality and reduce the cost of manufacturing gears, primarily for aerospace applications. Nanlawala has a degree in mechanical and aerospace engineering from Illinois Institute of Technology, Chicago. He is a registered professional engineer (P.E.) in the state of Illinois. He is also a certified manufacturing engineer (CMfgE) with the Society of Manufacturing Engineers.

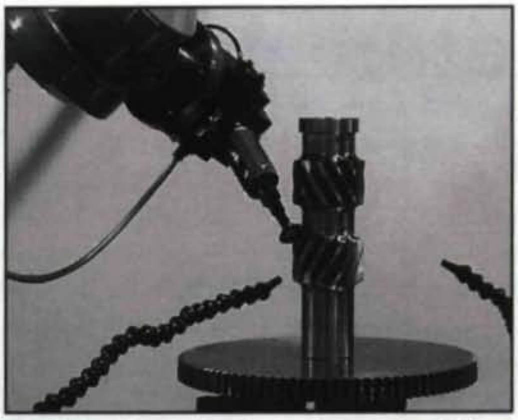

Fig. 2—The Single-Axis Compliant Head (SACH) from ABB deburring a double helical pinion.

ty of stress concentration and increases fatigue life.

Aerospace gears are usually precision ground to AGMA quality 12 to 14. For such gears, in addition to the required deburring of gear teeth, there are also very specific chamfering requirements, such as edge waviness and chamfer depth variability, surface finish, and the absence of under- or over-tempering of the deburred edges. Chamfer width must also be uniform along the entire gear tooth profile, as well as the root radius.

As mentioned earlier, wherever feasible, gears are deburred using relatively simple mechanical equipment. However, those machines lack the dexterity and the programmability that are essential to meet the specific chamfering needs of the usually complex-shaped aerospace gears. In general, such machines do a satisfactory job deburring and chamfering spur gears and helical gears with smaller helix angles, provided that the shape and size of the gear do not create an accessibility problem for the cutter, grinding wheel or grinding disc. In some cases, it is also feasible to deburr and chamfer helical gears with higher helix angles and spiral bevel gears using such mechanical equipment. However, to meet the specific chamfering requirements, the semi-chamfered gears need to be touched up manually after the automated operation. Further, secondary brushing operations are sometimes required to meet other chamfer requirements, such as edge radiusing and surface roughness. For those reasons, most aerospace gears are currently deburred and chamfered manually.

In a typical manual deburring and chamfering operation, a skilled operator removes material with a rotary file or a rotary grinding wheel or disc attached to a hand-held air driven or electrically powered tool.

Manual deburring is tedious, boring, laborious, very time consuming and thus very expensive. Manual deburring also produces inconsistent and often unsatisfactory results. Furthermore, manual deburring is ergonomically and environmentally undesirable, causing safety hazards, such as minor cuts, splinters, burns, bruises, and eye injuries. It may also cause long-term health hazards, such as arthritis, carpal tunnel syndrome, and illnesses associated with dust inhalation. Other disadvantages of manual deburring include a high rate of rework or scrap, additional inspection costs, lower productivity, high worker turnover, and high training cost to train new workers.

In a manual deburring situation, finishing operations can represent up to 20 percent of total production costs. Therefore, automating the deburring process can result in significant cost reduction, productivity improvement, and quality enhancement of deburred edges.

Robots are emerging as an economical solution to automating many types of processes. Historically, when robots were applied to less precise finishing operations like brushing, they have been shown to achieve more than a 50 percent reduction in processing times. Still, until recent improvements were developed, their accuracy has been prohibitively poor for use in the precision deburring of contoured edges. Those technological improvements include the introduction of precision robots having better than ± 0.004-inch repeatability and the development of deburring heads like the CADET (Chamfering and Deburring End of Arm Tool) and other commercially available force-controlled heads.

The strategy behind a force-controlled head is to use an industrial robot as a coarse positioning device, which carries and orients the force-controlled head to the appropriate part edge to be deburred and chamfered. Fine motion capabilities of the force-controlled head allow the tool to track edges based on force control, so that edge contours can be traversed and precise chamfer depths maintained in spite of unknown process variables including the robot's positional inaccuracies, deviations in part geometry (or contour), and fixturing errors. Force control has the added benefit with respect to gears of reducing the potential for grinding burn.

Robot Selection

Robots are available in different types and sizes. Most robots can be categorized into one of a few basic groups such as single-axis, multi-axis, SCARA (selective compliance assembly robot arms), Cartesian, cylindrical, etc. A minimum of six axes of movement is necessary to arbitrarily position and orient a tool and is therefore required to deburr the more complicated geometries of gears such as spiral bevels. The six-axis robot also makes it easier to manipulate the cutting tool to reach difficult access areas, such as narrow grooves, the very limited space between two gear faces or an adjacent shoulder and the gear face. As far as the robots are concerned, gear tooth deburring is a precision operation. Therefore, a robot selected for deburring preferably should have better than ± 0.003-inch repeatability. Furthermore, to minimize deflection, the robot arm should be more rigid than is required for most other operations. Stated another way, the end-of-arm payload capacity of the robot should be large enough that, under the weight of the end effector, deburring head, and cutting tool, the deflection of the arm will be minimal. A robot selected for the purpose of deburring should have its rated payload capacity preferably at least 50 percent higher than the maximum anticipated load at the end of the arm.

Considering the above factors, an ABB Flexible Automation robot, model No. IRB 2400/10, was selected for this study. The robot has a new S4 controller with the Rapid™ programming language. This robot's end-of-arm payload capacity is 10 kg, or approximately 22 lbs., and the reach of the arm is 59 inches.

Deburring Head Selection

While the robot itself is responsible for coarse positioning and orientation of the deburring tools, a specialized deburring head is needed to perform the actual processing. The deburring head functions much like a wrist at the end of the robot arm. The heads have either pneumatic compliance or electromagnetic force control that allows the cutter to "float" on the part edge and control the material removal rate. The head is thus able to adjust to process variations, including robot positional errors, part errors, fixturing errors and burr size to perform uniform material removal and minimize cutter loading, cutter wear and part burning.

Many deburring heads are available, and a large number were investigated. Three in particular yielded interesting results and will be discussed here. They included the Navy-developed CADET head, a single-axis compliant head (SACH) from ABB Flexible Automation, and a two-axis compliant head (TACH) from ABB. The SACH system is capable of being fitted with two different types of cylinders, one low-speed option (15,000 rpm to 40,000 rpm) and one high-speed option (45,000 rpm to 85,000 rpm). The low-speed option was used for deburring pinions, while the high-speed option was applied to gears. Another option considered early in the project was a high-speed, axially compliant device from ATI Industrial Automation. However, it was eliminated in preliminary assessments based on unacceptable surface finish and tool life.

The CADET head is not commercially available, and only a few prototypes exist. It has closed loop force control, making it easier to program since the trajectory points do not need to be as exactly specified. It also offers the best control over the material removal process because it operates in a closed force-feedback loop. The other two heads investigated are commercially available, off-the-shelf equipment and therefore less expensive to acquire, operate and maintain. The commercial heads also provide more options in cutter selection and allow operation at higher speeds than the CADET.

The CADET is a dual-axis force control head that uses a 5,000 rpm to 6,000 rpm electric spindle mounted within a force transducer assembly. The force transducer assembly is mounted within a two-axis gimbal that permits movement of the cutter tip in a direction perpendicular to the spindle axis over a 5-square centimeter work area. The gimbal is instrumented with position transducers in two axes, which enable measurement of cutter tip position. A unique dual-axis direct drive actuator, mounted above the transducer assembly and linked to the cutting process through the two-axis gimbal, provides the power for the cutting force control. The entire design is balanced gravitationally and dynamically in any orientation to minimize sensitivity to forces other than the cutting forces.

The CADET is controlled using a high-bandwidth, high-accuracy force servo loop. Fine motion capabilities of the CADET allow the cutter to track edges and control the material removal process based on force feedback, so that edge contours can be traversed and precise chamfer depths maintained in spite of process variations.

The SACH and TACH that were evaluated are produced by ABB Flexible Automation of New Berlin, Wisconsin. The range of motion for the SACH is ± 3.6°. Pneumatic grinders of the user's preference can be mounted in the head, including reciprocating filing tools or spindles of various speeds and configurations. In the present study, the SACH was fitted with various speed pneumatic spindles (15,000 rpm to 85,000 rpm) and used in conjunction with carbide cutters or grinding discs. It is shown in Figure 2. The TACH has ± 4 mm of two-axis radial pneumatic compliance and incorporates a 40,000 rpm or 85,000 rpm pneumatic grinder.

Cutting Tool Selection

The final component in the automated deburring system, after the robot and the deburring

Table 1—Process Development Findings[1].

	2" RexCut™	1" RexCut™	1" CBN	3/16" Cylindrical Carbide Cutter	90° Conical Carbide or CBN Cutter
INFAC Spiral Bevel Pinion	SACH[2] • Uniform Chamfer • Good Surface Finish • Good Burr Removal	Limited Cutter Life	Not Tested	Not Tested	CADET • Uniform Chamfer • Rough Surface Finish • Good Blending
***INFAC LH 35°* Helical**	SACH • Uniform Chamfer • Good Surface Finish • Good Burr Removal • Blending Issues	Limited Cutter Life	Not Tested	Feature Interference	CADET • Feature Interference • Large Burr/Cutter Ratio
02035-12130-101 Double Helical (Bull Gear)	Feature Interference	Feature Interference	Feature Interference	TACH[3] • Uniform Chamfer • Good Surface Finish	Feature Interference
02035-12137-101 Double Helical Pinion (Sikorsky)	Feature Interference	SACH • Uniform Chamfer • Good Surface Finish • Good Burr Removal • Blending Issues	SACH • Uniform Chamfer • Questionable Surface Finish • Good Burr Removal • Good Cutter Life • Blending Issues	TACH • Uniform Chamfer • Good Surface Finish	Feature Interference
70351-38171-101 Spur	Not Tested	Limited Cutter Life	Not Tested	Feature Interference	ATI Turbac • Feature Interference • Rough Surface Finish • Non-uniform Chamfer
0351-08221-101 Spiral Bevel	Not tested yet. Anticipate similar success as 70358-06620-102	Limited Cutter Life	Not Tested	Feature Interference	Large Burr/ Cutter Ratio
70358-06620-102 Spiral Bevel	SACH • Uniform Chamfer • Good Surface Finish • Good Burr Removal • Limited Cutter Life	Limited Cutter Life	SACH • Uniform Chamfer • Some Cutter Loading • Some Teeth Experienced Chatter	Feature Interference	Large Burr/ Cutter Ratio

Footnotes
1. Shaded regions indicate processes that show feasibility.
2. SACH: Single-Axis Compliant Head
3. TACH: Two-Axis Compliant Head

head, is the actual cutting tool that physically removes the burrs from the gears and applies the chamfers. A variety of cutting tools were investigated, including:

- 2-inch RexCut™ disc cutter,
- 1-inch RexCut™ disc cutter,
- 1-inch CBN (cubic boron nitride) disc cutter,
- 3/16-inch cylindrical carbide cutter, and
- 90° conical cutter (carbide and CBN).

Various combinations of deburring heads and cutters were tested on several different gears, and a number of output parameters were observed. They included surface finish, chamfer uniformity, blending, cutter life, and overall quality of the process. The results and observations for those tests are summarized in Table 1. In it, each row represents one of the specific gears that were investigated. Each column represents one of the cutting tools used. Within the body of the table, for each gear/cutter combination, an assessment is listed as to whether that tool could be used with that gear or not, and if so, which head was utilized and what results were achieved. Successful combinations, demonstrating feasibility of the automated deburring process, are indicated in the table via shading.

As can be seen in Table 1, not all gear/cutter combinations proved to be successful. The cutter must access the gear tooth profile without hitting adjacent features. It must also have the required material removal capabilities and wear properties, and it must produce an acceptable surface finish. A lubricant, Aculube™, was used in most of the cutting trials. It was found to improve surface finish and extend the life of the cutter. The conclusion from this set of tests is that the cutters, more than the compliant heads that carry them, determine the success or failure of the processing procedures.

Excellent results have thus far been achieved with 0.040-inch thick grinding discs of the RexCut™ product. The cutters are the same as those currently used in the industry for gear finishing using non-robotic equipment. They are aggressive and fit well into small root radii. They produce very good surface finish and uniform chamfers. The larger diameter RexCut™ products (2-inch diameter or greater) have sufficient life and fit within the features of many of the more complex parts. Using the cutters with a compliant head and a robotic positioning device greatly enhanced their usefulness. Unlike most machines being used currently for gear deburring, the robot permits optimal orientation and positioning of the cutters for each feature being processed. The compliant heads provide force control to protect the gears from grinding burn, to extend cutter life and to adapt to inherent positional errors of a dexterous robot.

Parts like the double helical bull gear do not permit the use of those discs due to interference with adjacent features. Luckily, carbide cutters were shown to be successful for the gears.

The CBN (cubic boron nitride) discs under investigation, while not suffering from the cutter life problems of the RexCut™ discs, do produce a rougher (yet most likely acceptable) surface finish, and some cutter loading and chatter were observed. Future work should develop the process parameters for improving the deburring process with the CBN cutters.

Path Programming

In addition to component selection, the programming of motions is an essential step in the development of an effective automated deburring system. Since the INFAC system is robot-based, a robotic type of path programming algorithm was used.

Figure 3 illustrates the typical nomenclature used in programming most of the gear paths for this study. Each tooth edge—that is, the obtuse edge and the acute edge—was programmed using one or two points at the root (either a single pRM or both pRMO and pRMA), a point near the root but on the tooth profile (pEAPO and pEAPA), a point at the midpoint of the profile (pMAPO and pMAPA), a point at the outer end of the profile (pSAPO and pSAPA) and one or two points at the nose of the gear (either a single pNOS or both a pNOSO and pNOSA).

Those points were programmed using the teach pendant by first finding an orientation for the head/cutter that is accessible to all points on a tooth side (acute or obtuse). Next, each point is jogged to and taught. If deburring is being performed with a carbide cutter, then cutter abrasion is not an issue and each point is programmed into the edge (depressing the compliance) by 1 mm to 2 mm. Thus, when the program is executed, the compliance of the head should be depressed to a depth of 1 mm to 2 mm throughout the cut. In the case of an abradable cutter like the RexCut™ wheels, the cutting depth bias is addressed using the robot programming language's RelTool function, which is used to permit program offsets in the direction of wear. In this case, the points are taught by jogging the robot to a position just touching the edge. The compliance depth programmed using the RelTool function then drives the disc into the edge (against the compliance) in the compliance direction of the tool (head) coordinate system.

The cutter orientation was chosen to be roughly perpendicular to the bisector of the edge at the midpoint of the tooth profile, i.e. the edge normal. However, for a helical or spiral bevel gear tooth, that means the acute profile generally requires a different cutter orientation than does the obtuse profile. That is why currently available non-robotic deburring machines with fixed cutter orientation cannot produce a uniform chamfer on both sides of such gear teeth. It would be preferable to reorient the cutter in the root so that the acute side and the obtuse side both have their own optimum orientations and there is one continuous cut. Unfortunately, early trials showed that the increase in robot dynamics associated with reorienting the robot produced divots in the gear tooth edge. The efforts of this study have, therefore, focused on programming trajectories that maintained a constant head/cutter orientation throughout the cut, per side. A natural consequence of not changing the orientation during the cut is that there will be a region of each tooth edge where a blend from one cut to the next must take place (usually in the root).

It may be possible to develop a means of reorienting with minimal dynamics. Approaches might include adjusting the maximum permissible reorientation speed or playing with the zone data (both position and orientation). Also, one must use care that the tool center point (TCP) is accurately defined when making reorientations while cutting.

It is important in programming with a robot to allow for both static and dynamic robot error in fixturing, cutter, part, and other process errors. Thus, the programmer is always thinking about the worst case positional errors and allotting clearance for such errors. For example, in programming a start point between two teeth, one should leave sufficient room between the cutter and adjacent features to account for possible process errors. With modern robots, this typically requires a minimum clearance of 0.03 inches.

One should also take advantage of inherent degrees of freedom in the system to allow room for error. For example, in programming for flank milling cutting with a cylindrical cutter, the three

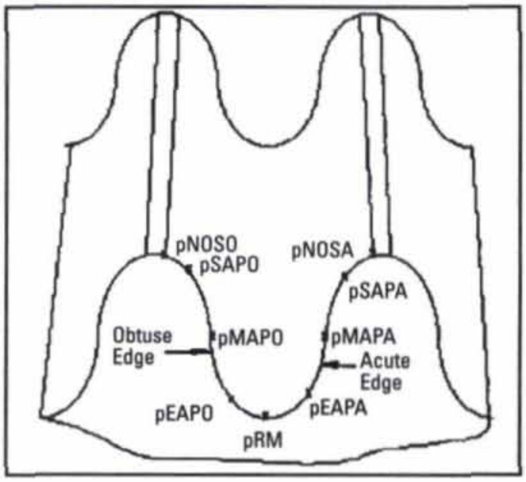

Fig. 3—Programming nomenclature used to program gear tooth profile.

Table 2—Double helical bull gear processing parameters.

Cutter	Head	Grinder Rotational Speed	Feed Rate Override	Compliance Pressure	x, y, z Euler Angles (degrees)	Automated Processing Time	Time Savings
3/16" Ball End Cylindrical Cutter MA Ford 42187530	ABB 40/240 2-axis Head	Approx. 35 krpm Free Speed	30% Override	40 psi	Acute -138.98 -6.77 -131.578 Obtuse -177.987 31.739 133.227	2 hours	10 hours

degrees of freedom for positional errors are accommodated as follows:

- Errors along the axis of the cutter are accommodated by symmetry along the axis of the cutter.
- Errors normal to the edge are accommodated through compliance in the head.
- Errors along the tangent to the edge are accommodated by the fact that they are aligned with the direction of feed.

In programming the disc cutter:

- Errors tangent to the disc at the point of contact are accommodated by symmetry at this point.
- Radial errors are accommodated by compliance in the head.
- Errors perpendicular to those are accommodated by the fact that they are aligned with the feed direction.

It was found that a better blend at the root between the acute and obtuse sides of the tooth could be achieved with a layered approach. That could be done, for example, by starting with a cutting pass on the acute side of each gear tooth, then a pass on the obtuse side of each tooth, then a final finishing pass on the acute side. Also very important to achieving a good blend is that the chamfer angles from the acute and obtuse passes must match as much as possible over the blending region.

Selectively cutting the acute and obtuse edges has the added benefit of permitting the operator to incorporate that selectivity into the final operator program. Thus, the program could be made to allow the operator to selectively choose to make another pass on the acute or obtuse side, depending on which looked as though it needed another pass. Keep in mind, though, that switching back and forth is the best way to accomplish a smooth blend. Making too many passes on one side without finishing with a final pass on the other side can leave a noticeable divot at the start point. Fortunately, the deeper the chamfer is, the less the chamfer opens per pass because the force is proportional to the area of the cut.

Example: Double Helical Bull Gear

One of the most challenging of the gears tested in this investigation was a 30-inch diameter, 10-diametral pitch, double helical bull gear. That particular gear has two helical gear surfaces, separated by a gap of approximately three-quarters of an inch. Processing parameters that were found to work effectively are summarized in Table 2. In that table, the compliance pressure is measured close to the deburring head. The *x*, *y* and *z* Euler angles give the orientation of the tool coordinate system with respect to the robot base coordinates.

After a manual deburring operation, the bull gear had an inconsistent finish and many divots. After processing with the automated deburring system, the edges were smooth and uniformly chamfered. Time spent to deburr this gear manually was approximately 12 hours. Time to deburr using the automated system was approximately two hours, or a savings of 10 hours, about 80 percent.

Example: Double Helical Pinion

Another challenging gear to deburr was the pinion that drives the bull gear in the example above. That pinion contains two helical surfaces, approximately 2.5 inches in diameter, also a 10-diametral pitch with a 35° helix angle and a three-quarter inch gap. There is also an integral 10-inch diameter spur gear on the same shaft.

The double helical pinion was processed using the 3/16-inch carbide cutter. The burrs were not an obstruction to the process and a uniform chamfer was produced in spite of them. Time to process the gear was reduced from 150 minutes for manual operation to 15 minutes for automated operation.

Chamfering Results

Another issue of interest is chamfering quality and uniformity. The automated deburring system has been applied to different types of aerospace gears including:

- 10-diametral pitch spur gears,
- 35° and 45° helical gears,
- 35° double helical pinions and gears, and
- 4- and 5-diametral pitch spiral bevel gears and pinions with 30° and 35° spiral angles.

Figure 4 shows data on the results of cutting some of the more challenging gears and pinions. The plot shows the average, maximum and minimum chamfer widths measured for all teeth. Because the maximum and minimum chamfer width did not exceed the typical ± 0.010 inch tolerances and the surface finish was good, the process was deemed successful.

Admittedly, the acute edge came out smaller than the obtuse edge for several of the gears. The goal of the testing was not to produce the correct chamfer width so much as to achieve acceptable chamfer width uniformity and surface finish. Once the uniformity is achieved on each side, the chamfer widths can be matched by changing the number of passes across the acute or obtuse edge or by adjusting other parameters like the cutting force or feed rate.

Future Work

The results presented here represent interim findings of an ongoing project at INFAC, the Instrumented Factory for Gears. One of the goals of this initial part of the project was to assess the feasibility of developing an automated deburring system for aerospace gears. To that extent, this phase has been considered successful. The feasibility of the automated system was demonstrated by deburring different sizes (from 3-inch to 30-inch diameters) of spur, helical, double helical and spiral bevel gears and pinions. For this purpose, a six-axis robot, a programmable indexing table and commercially available deburring heads were utilized. Such a simple system was more than adequate to conduct the feasibility study. However, for such a system to operate more efficiently in a production setting, a number of improvements in areas like programming, fixturing, cutters and cutting parameters may be necessary. A brief list of potential areas for future work follows.

Offline programming. Programming the robot offline can increase the robot's productive time and also reduce development or prove-out time considerably, since any unexpected problem in fixturing, path programming, or operating the robot can be detected and resolved before the robot is loaded with the desired program.

Tool wear compensation. To maintain consistency in the width of the chamfer, it is necessary that the cutting tool diameter remains constant. That is not a problem with cylindrical cutters. However, when very thin, fiber-bonded RexCut™ discs are used, an appreciable amount of tool wear is experienced. That tool wear must be compensated for, and that can be accomplished by a simple touch probe.

Application of CBN cutters. Another approach to handle the tool wear problem is to use longer CBN-coated disc cutters. In the feasibility phase, such cutters were used on a limited basis. More development is required in that area.

Brushing operations. In the case of gears being deburred after hardening and grinding, brushing is often necessary to remove minor secondary edges and also to improve surface finish. In such cases, brushing is normally performed manually. That expensive manual brushing could also be eliminated by integrating brushing with robotic deburring and chamfering.

Automatic tool changes. To accommodate different types and sizes of gears, it may be necessary to use various deburring heads and cutters. In such cases, setup time or changeover time can be reduced and the robot's actual productive time increased by integrating some sort of automated tool changing system. A number of manufacturers have developed such systems, and they could be integrated into the robotic deburring system with little trouble.

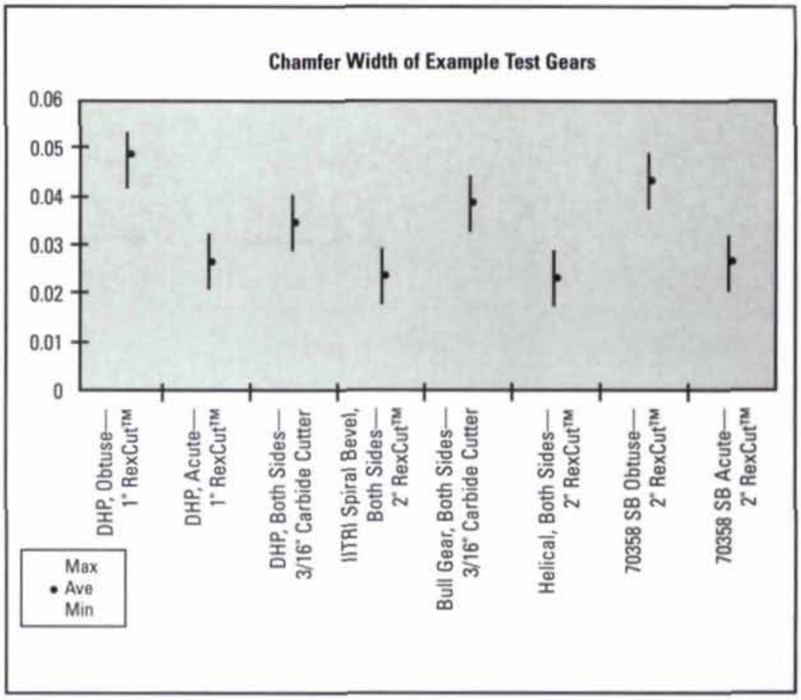

Fig. 4—Chamfer width and consistency from tooth to tooth for various test gears and processes.

Conclusions

The following conclusions can be summarized for this project, based upon work performed to date:

- Robotic automated deburring of aerospace gears is feasible and has been demonstrated on spur, helical, double helical, and spiral bevel gears from 3 inches to 30 inches in diameter.
- Both deburring and chamfering of aerospace gears can be achieved with an automated system.
- A successful automated deburring system for gears can be constructed from commercially available, off-the-shelf components.
- Quality and consistency of deburred and chamfered edges were increased in gears processed with the automated system, as compared with manually processed gears.
- Careful cutter selection is essential to achieving high-quality automated deburring.
- Process time for automated deburring was often as much as 90 percent shorter than manual deburring.
- Cost savings achieved through automated deburring, primarily through time savings and scrap reduction, is estimated at an average of 65 percent, as compared with manual deburring. ○

Tell Us What You Think . . .

If you found this article of interest and/or useful, please **circle 206.**

If you did not care for this article, **circle 207.**

If you would like to respond to this or any other article in this edition of *Gear Technology*, please fax your response to the attention of Randy Stott, managing editor, at 847-437-6618.